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Report of the Expeditions from the Royal Observatory, Greenwich, to observe the Total Solar Eclipse of 1927 *June* 29. (Plates 8–12.)

(*Communicated by the Astronomer Royal.*)

1. A site in the neighbourhood of Settle was considered desirable as being near the central line, easy of access for large instruments, and where accommodation could be readily found for the observers. The exact position was determined by the offer of the Governors and Headmaster of Giggleswick School to place a field near the school chapel at the service of the Astronomer Royal. From this point the hills to the east rise to a height of 4° to 6°. Though this might be to some extent a drawback, the practical gain of having a place where the instruments would be safe and the observers free from interruption and within easy reach of an hotel in Settle more than compensated for this slight disadvantage.

The programme of observations included a large-scale photograph of the corona, observations of the extreme-red end of the chromospheric spectrum, and a comparison of the intensities of the calcium lines in the infra-red with those at H and K. An addition to the programme was made by the offer of the Editor of the *Daily Mail* to place an aeroplane at the disposal of the Astronomer Royal. This practically ensured that a photograph would be obtained giving the general form of the corona in the event of clouds covering the whole zone of totality at the time of the eclipse. A further addition to the observatory programme was made by the offer of the Hydrographer of the Navy to find accommodation for observers on the survey ship H.M.S. *Fitzroy*, which was engaged at the time of the eclipse in the North Sea near the zone of totality. This added another chance in the event of cloudy weather.

2. The instruments taken to Giggleswick were—

(*a*) A 6-inch lens of 45-feet focus, made by Alvan Clark and kindly lent by Mr. J. H. Worthington. This was mounted horizontally in a long tube of steel lattice-work, covered with black cloth and Willesden canvas. It was fed by an 8-inch cœlostat belonging to the Royal Irish Academy. The plates employed were Ilford Special Rapid of 15×12 inches.

(*b*) A spectroscope of small dispersion for direct comparison of the intensity of the ionized calcium lines in the infra-red with those at H and K. This was of a reflecting Littrow type. The light, after passing the slit, was directed by a diagonal reflector on to a $6\frac{1}{2}$-inch concave mirror of 38-inch focus. From here it was sent back as a parallel beam to a 30° prism silvered on the back. This, after refraction and reflection, returned it to the mirror from whence it was reflected to focus on the photographic plate at a point just above and beyond the prism. Good definition was secured from λ3900 to λ8600.

The sun's image was formed on the slit plate by a 9-inch concave speculum mirror of 10-feet focus, which was filled with light from a 16-inch cœlostat.

The complete optical train thus consisted of three disconnected parts—the cœlostat, the image-forming mirror, and the spectroscope—which must be brought into simultaneous adjustment. As their relationship is changing with the varying declination of the sun, under the weather conditions prevailing this adjustment proved most difficult.

By means of a coarse wire grating which could be slipped in front of the prism, an intensity scale was placed on the plate by exposures on the solar spectrum, made just before and just after totality.

Specially prepared infra-red sensitive plates were used, but although on experimental plates before and after the eclipse λ9000 was reached without difficulty, yet the plate exposed during the eclipse proved insensitive beyond λ8000. Consequently the observation failed in its purpose.

(*c*) A spectroscope of greater dispersion for more detailed examination of the chromospheric spectrum in the extreme red. This also was of Littrow type. The prism was of 40° angle and 7 inches height, whilst the collimating lens was of $7\frac{1}{2}$ inches aperture and $11\frac{1}{2}$ feet focal length.

As with the small spectroscope, the image on the slit plate was formed by a 9-inch concave speculum mirror, kindly lent by Sir John Herschel, filled from a 12-inch cœlostat. On experimental photographs excellent definition was obtained from λ5000 to λ8000, but owing to the unfavourable conditions obtaining at the time of the eclipse no results of value were obtained with this instrument.

The instruments were all set up at Greenwich a few weeks before the eclipse.

3. The observers were Dr. Jackson, Mr. Davidson, Mr. Melotte, and Mr. Woodman. They saw the instruments duly dispatched on an Admiralty lorry on June 13. Mr. Davidson and Mr. Woodman left the following day, and arrived at Giggleswick in time to choose the positions for the various instruments and developing hut. Dr. Jackson

and Mr. Melotte followed the next day, and reached Giggleswick about the same time as the lorry with the instruments. Mr. Greaves and Mr. Horrocks joined them on June 17 in order to give assistance and gain experience. The lorry was unloaded on June 16, and with the help of Mr. Brassington, a local contractor, whose services were engaged, the instruments were carried into the field in small loads and got under cover. The instruments were erected under difficult conditions owing to rain and wind. Still more difficult was the adjustment, as there were few occasions on which the sun was visible for many minutes consecutively. At the hour of the eclipse the sun was visible in a clear sky on June 15. For 13 consecutive days clouds obscured the sun at this time.

The 45-foot telescope was focussed visually by an autocollimating method. A plane mirror—the mirror from its own cœlostat—was set just in front of the objective and normal to the optical axis of the lens. By observing, through cobalt glass, the reflected image of a lamp placed near the focal plane the focus could be determined with great certainty.

The focus of the spectroscopes was determined by photographing the calcium spark obtained with a coil and storage batteries which had been taken for the comparison spectra. The final focussing adjustments were made on the night of June 28.

The party was joined at Giggleswick by M. Maxime de Saussure, for whom a 3-inch telescope, fitted with a direct-vision prism placed before the object-glass, had been provided. He proposed to observe the times of beginning and end of totality by disappearance and reappearance of the absorption lines of the chomosphere.

At their request, representatives of four cinematograph firms were permitted to take stations in the field assigned to the observatory party, viz. Gaumont, Pathé Frères, Topical Budget, and British Polychromide Ltd. (a colour process). We were very pleased to give these facilities in view of the educational value of the films. An object-glass was lent to Pathé Frères to give a large-scale image, and a second mirror, kindly lent by Captain Ainslie, was mounted on the cœlostat supplying the 45-foot telescope. The use of the cœlostat mirror was suggested as it admitted of greater stability for the cinema apparatus, but there was too little time before totality to get this mirror into adjustment, so the photographs were taken directly.

4. On the evening of June 28 the weather showed some signs of improvement. Mr. Davidson and Mr. Melotte went to the field after dinner on that day and stayed there the night, bathing plates and filling plate carriers, and verifying some of the adjustments of the spectroscopes. They were joined in the early morning by the Astronomer Royal, Dr. Jackson, Mr. Woodman, and Mr. Horrocks. At this hour people were gradually collecting in the neighbourhood. The field assigned to us was guarded by the School O.T.C. and a few policemen, and none was allowed in except those to whom passes signed by the Astronomer Royal and the Superintendent of Police had been given. These included, besides the official party, several parties of amateur astronomers, cinematograph operators, press representatives, and photographers. There were a few breaks in the clouds, but it was

not till about 10 minutes before totality that the sun was more than momentarily visible. Mr. Horrocks with a chronometer, whose error had been determined from the B.B.C. signals, called out from the calculated times 10^m, 5^m, 2^m, 1^m, 50^s, 40^s, 30^s, 20^s, 10^s before totality. Mr. Davidson gave the word " Go " as the crescent broke into beads, and Mr. Horrocks took up the counting of seconds, and the plates of the several instruments were duly exposed.

The rapidity with which the crescent disappeared and the brightness of the corona were generally noted. Red prominences particularly near the vertex of the sun were visible to the naked eye. The duration of totality was generally estimated at 23^s, though no precise observation was attempted.

The time of second contact was observed, and for comparison with the computed time Col. Jack, Director-General of the Ordnance Survey Office, Southampton, has kindly communicated the position of the site at Giggleswick as follows :—

Latitude . . .	54° 4′·2 N.
Longitude . . .	2° 17′·7 W.
Altitude . . .	570 feet.

The sun was at an altitude of 12°·1 in azimuth 23°·2 N. of E., so that the shadow reached the camp at the same time as it reached sea-level in

Latitude . . .	54° 4′·0 N.
Longitude . . .	2° 18′·4 W.

This position is only about 0·2 of a mile north-west from the central line as given by Dr. Comrie in *M.N.* **87**, 496. From Dr. Comrie's data the computed time of mid-totality was $5^h\ 24^m\ 28^s{\cdot}9$ G.M.T., so that if we take the duration of totality as $23^s{\cdot}4$, the computed beginning was $5^h\ 24^m\ 17^s{\cdot}2$. When Mr. Davidson said " Go " the chronometer showed $5^h\ 25^m\ 0^s$. The correction to the chronometer was $-44^s{\cdot}5$, so that this corresponded to $5^h\ 24^m\ 15^s{\cdot}5$ G.M.T. The Astronomer Royal with the chronometer before him noted that the beginning of totality was at $5^h\ 25^m\ 0^s$. This agreed with Mr. Davidson's " Go," which he estimated might be as much as $0^s{\cdot}5$ early. The Astronomer Royal's observation, therefore, indicates that the eclipse commenced $1^s{\cdot}7$ early and Mr. Davidson's $1^s{\cdot}2$ early. The photograph of the corona was taken from $5^h\ 24^m\ 17^s$ to $5^h\ 24^m\ 36^s{\cdot}5$ G.M.T. It is clear that the eclipse took place at least one second before the computed time. M. de Saussure, as seen from the following paragraph, made the eclipse begin $1^s{\cdot}1$ early, so that the mean may be taken as $1^s{\cdot}3$ early.

M. de Saussure's report is as follows :—

" I observed the eclipse with the Greenwich party, in the chapel field at Giggleswick, and used a 3-inch refractor kindly put at my disposal by the Royal Observatory ; in front of the object-glass a direct-vision prism was mounted. I had to observe inner contacts by means of the flash spectrum (with Nardin stop watches to be compared with the chronometer). The observations were made in the green part of the

spectrum. I saw the first reversal, from the dark to bright lines, at $5^h\ 24^m\ 16^s{\cdot}1$ G.M.T., which must be the time of second contact. The time of third contact could not be determined, because the lines showed the interesting feature of remaining bright several seconds after totality.

"During totality I looked at the corona with a field-glass and noted its type as nearly corresponding to maximum of sunspots, with an outline showing several projections finishing in points."

No meteorological observations were made by the Greenwich party. As the eclipse occurred in the early morning when temperature would normally be rising there was nothing sufficiently large to notice without a thermometer. The darkness during totality was just sufficient to necessitate the use of a flash-light in reading the chronometer.

Among the minor observations the visibility of the corona before and after totality may be noted. Dr. Jackson with the naked eye saw it extending along 90° of the limb opposite to the crescent 25^s before the total phase without having specially looked for it.

The photograph of the corona was developed on the spot by Mr. Melotte, and at ten o'clock was photographed by a representative of the *Evening News*. It was taken to London by aeroplane and appeared in the *Evening News* the same day, and in several of the London morning papers on June 30. A number of photographs on a small scale were taken by amateur observers and by the press photographers. Among these are excellent ones by Dr. Waterfield and by Mr. Warhurst of the *Times* photographic staff. These show the type of the corona and its extensions. By the courtesy of the Editor of the *Times* the latter is reproduced in this paper (Plate 11).*

5. *Aeroplane Observations.*—With the object of ensuring some observations of the corona in the event of cloudy weather, the *Daily Mail* placed an Imperial Airways twin-engined, fourteen-seater aeroplane at the disposal of the Astronomer Royal, and Mr. Greaves and Mr. Witchell, together with Mr. F. J. Hargreaves, formed the observing party. Two cameras were installed in the machine; one being a Ross portrait lens of 16 inches focus, working at F/4·5, and the other an Aldis lens of 20 inches focus, working at F/5·6. The latter camera was kindly lent by Dr. G. Merton. Mr. Witchell was in charge of the Ross camera, which was mounted on the roof of the machine and manipulated from the passenger saloon through an emergency safety-hatch, the cover of which had been removed. The Aldis lens was manipulated by Mr. Greaves and was mounted on a table installed in the saloon and operated through one of the windows, the glass pane of which had been removed. These arrangements were decided on as the result of a trial flight and were effected in the shops of Messrs. Imperial Airways, Limited, at Croydon Aerodrome. Shock-absorbing material was used to deaden as far as possible the vibration due to the engines.

The machine with the observers and two *Daily Mail* representatives left Croydon on the evening of June 28, under the pilotage of Captain F. L. Barnard, and proceeded to Catterick Aerodrome. The eclipse flight commenced at 4·20 a.m. (Greenwich Mean Time) on June 29.

* Dr. Waterfield's photographs are reproduced on Plate 16.

Captain Barnard flew to Hartlepool, and, having from this flight obtained his allowance for wind-drift, climbed above the clouds and flew by dead reckoning south-west along the eclipse track. The altitude at the time of totality was 11,700 feet.

Mr. Witchell secured an exposure on the corona at 1/50th second, and Mr. Greaves one at 1/30th second. These are reproduced (Plate 11). The first has "trailed" slightly and shows the general form of the inner corona very well. The second, although badly shaken, shows an extended corona up to over a diameter from the limb. The plates used were hypersensitized panchromatics, with a speed of about H and D 1300, prepared by Mr. Thorne-Baker of the Imperial Dry Plate Co. They had been obtained from Mr. Thorne-Baker by Mr. Hargreaves. Mr. Witchell also obtained an exposure at 1/15th second, using a backed Ilford Special Rapid plate. This is not reproduced but clearly shows eight or nine prominences. Mr. Hargreaves had planned to photograph the shadow on the ground, but was frustrated by clouds which extended up to over 10,000 feet. He obtained, however, a photograph showing the near cloud clear of the approaching shadow and distant clouds in it, and clear sky on the far side of the shadow.

There was a large amount of cirrus cloud about at a high altitude, but Captain Barnard by skilful navigation placed the aeroplane at the time of totality in such a position that the view of the sun was unobscured.

The two photographs reproduced have been studied carefully by Mr. Hargreaves, who has made a drawing from them. This is also reproduced (Plate 12).

It appears very probable that, as a result of the experience gained, better photographs could be obtained on a future occasion. It would seem that a suitable type of camera to use would be one of about 20 inches focus, working at about F/3, and using exposures of 1/100th second or even less on hypersensitized plates.

Any success that has been achieved is largely due to the splendid piloting of Captain Barnard, and the assistance received during the preparations from the staff of Messrs. Imperial Airways, Ltd.

6. *Observations in North Sea.*—Rear-Admiral H. P. Douglas, C.M.G., Hydrographer of the Navy, having found it possible for observers to be accommodated on one of H.M. surveying ships operating in the North Sea, Messrs. Edney and Chamberlain proceeded on board H.M.S. *Fitzroy*, commanded by Commander J. R. Harvey, O.B.E., R.N. They were accompanied by Lieut.-Comdr. C. P. Christie, R.N.

Their equipment consisted of two cameras, one fitted with the 6-inch Franklin-Adams lens of 27 inches focus; and the other with an Aldis lens of 20 inches focus, working at F/5·6, kindly lent by Dr. Merton. Each camera was fitted with gun-sights and specially mounted so as to allow a rapid setting on the sun to be made.

About midnight on June 28 the *Fitzroy* anchored in a position on the central line of totality in Lat. 54° 45′ 0″ N., Long. 1° 8′ 36″ W. On account of misty weather it was not possible to fix with any degree of accuracy a position further seaward. It also appeared advisable to anchor moderately close to the shore in order that the ship might remain

as steady as possible during the eclipse. At this time there was a slight northerly swell, sea calm, light airs, and mist over the land, Heugh Light being visible at a distance of about 3 miles.

A comprehensive programme had been drawn up and Comdr. Harvey had allotted each member of his staff some share in it. The items included observations of the second and third contacts, approach of the shadow, drawings of the corona, and meteorological observations. A watch was to be kept also for any planet or stars which might become visible during totality.

On the 29th the sun rose behind heavy banks of massed cloud and it soon became apparent that the expedition was doomed to failure. The *Daily Mail* aeroplane was observed manœuvring over Hartlepool, and during totality Jupiter was seen, through a slight break in the clouds, by Comdr. Harvey and by one of the crew who had been especially deputed to keep a look out for it. A glimpse of the partially eclipsed sun was obtained at $5^h\ 46^m$ and at $6^h\ 6^m$ G.M.T.

The thermometer readings taken between $4^h\ 20^m$ and $5^h\ 40^m$ G.M.T. showed a range of only 7/10ths degree Fahrenheit.

The observers wish to acknowledge their indebtedness for the great kindness shown to them by Comdr. Harvey and his staff and for assistance rendered them in every possible way.

7. *The Large-scale Photograph.*—The exposure of the large-scale photograph of the corona extends from one or two seconds after the commencement of totality to within one or two seconds of its termination. The picture it gives of the chromosphere and corona reaches to at least 1″ of the sun's photospheric limb in the equatorial regions and 6″ at the poles. It is thus of special value in showing the chromosphere all round the sun and the relationship of the lower corona to the prominences. All round the limb prominences are shown, the largest ones being near the north. The indentations on the limb indicate a large number of smaller prominences even where they are not distinctly shown in the photograph. Near the south point concentric arches in the corona are shown over a group of prominences. The brightest arch, about 30″ broad and of 2′ radius, is of approximately semicircular form with its centre near the limb. Inside this a smaller arch is shown, and outside, with radius of about $3\frac{1}{2}'$, a fainter arch can be seen on the negative.

The most remarkable features are near the east and west points. Here thin streaks and detached portions of prominences are shown and the corona has its greatest intensity. It would seem that the ionization found in the chromosphere is in these regions carried to a greater degree and forms coronal matter. The guess may be hazarded that strong bright lines in the corona spectrum would have been strongly shown in these regions. This may be inferred from the results of previous eclipses, that emission lines in the coronal spectrum do not extend far above the sun's limb and vary in different parts. Reference may be made to the green line as found in the spectrum taken in 1905 when the slit ran across a large prominence (*Phil. Trans.*, **206**, 403), and to the strength of the coronal rings in the neighbourhood of prominences in the eclipses of 1898 and 1926 (*Phil. Trans.*, **197**, 151; *R.A.S. Memoirs*, **64**, part 4). Attention may also be directed to the development of a bright patch of

corona in the position of a prominence in 1901 in the 100 minutes elapsing between photographs taken in Mauritius and Sumatra. These all confirm the view that the emission lines in the corona arise from matter in the neighbourhood of prominences possibly more ionized than the chromospheric material. The rest of the corona, possibly including the arches, gives a continuous spectrum, and probably arises from light reflected and scattered from small particles.

Patches of prominence matter which have been shot high above the photosphere and are detached from the main chromosphere can be seen in several places. The highest part is in position-angle 58° and is 3′·0 above the sun's limb. In a slightly smaller position-angle, 53° to 45°, is a narrow circular arc of prominence matter reaching 1′·2 above the photosphere. A fine vertical prominence is in 11° position-angle, the extreme height being 1′·2. This height of 1′·2 appears to be reached by prominence material in quite a number of places. The coronal matter in many places, especially near the equator, in position-angles 75° and 260°, is so bright that it cannot be readily differentiated from the prominences. Direct photographs of the sun taken at Greenwich on June 30 indicated a large spot on the sun near the position-angle 75° and a large amount of faculæ both there and at 260°.

8. *Small-scale Photographs.*—The corona is of maximum type, and the photographs show fairly strong extensions of the corona to a distance of one radius of the sun from the limb. The strongest of these is on the west side from position-angles 215° to 300°. At about 300° another branch of the corona can be seen whose edge makes an angle of about 120° with the last streamer. This branch extends from 300° to 20° and includes the large prominences near the north pole. Then follows another bright portion of corona, as bright as but not extending as far as the part from 215° to 300°. This extends from 30° to 115°. Two comparatively narrow streamers are prominent at 120° and 130°. Round the south pole between 135° and 215° there is a fairly uniform extension with the eastern edge more definitely marked than the western.

Reproductions are given of (1) the large-scale photograph slightly reduced, (2) east and west limbs on larger scale, (3) the photograph by Mr. Warhurst enlarged 2½ times, (4) two of the aeroplane photographs enlarged 3 times, and (5) the drawing made from them by Mr. Hargreaves.

Although a little outside the scope of this report, it seems desirable to draw attention to the great popular interest taken in this eclipse. This was largely brought about by the press, which drew attention to the rare occurrence of total eclipses and to the splendour and impressive nature of the spectacle. Railway facilities were arranged by the L.N.E.R. and by the L.M.S., so that many thousands were enabled to reach the zone of totality by rail. Many came by car or charabanc. The number who visited the neighbourhood of Settle was estimated by the Superintendent of Police as 100,000. Nearly all of these had a good view of the eclipse.

In conclusion, I wish to express my thanks to those who kindly lent instruments, particularly to Mr. J. H. Worthington ; to the Governors and Headmaster of Giggleswick School for the use of what the exigencies of weather made the best site in England ; and to the municipal authori-

East Limb.

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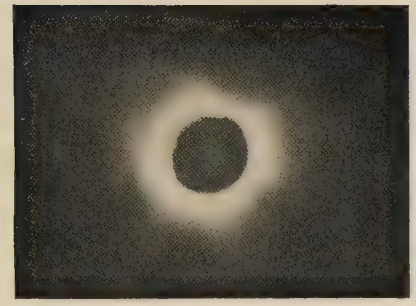
Aeroplane Photographs.



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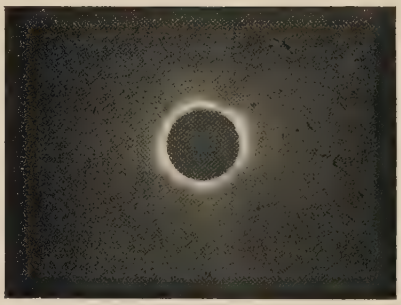

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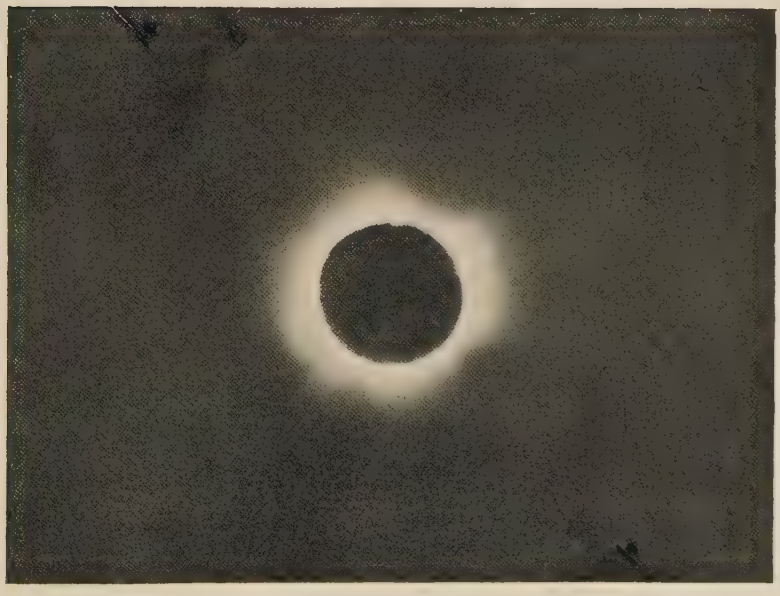


Photograph taken at Giggleswick by Mr. Warhurst.

Solar Corona, 1927 June 29. Drawn by F. J. Hargreaves, from aeroplane photographs.

ties of Settle and Superintendent of Police for the excellence of their arrangements in securing us from any inconvenience from intrusion on the ground. I also wish to thank the *Daily Mail* for providing an aeroplane, and Imperial Airways, Ltd., for valuable co-operation; and the Hydrographer of the Navy and the Commander of H.M.S. *Fitzroy* for their interest and assistance.

Total Solar Eclipse of 1927 *June* 29: *Report of the Oxford Expedition to Southport.* By H. H. Turner, H. Knox-Shaw, and H. G. S. Barrett. (Plate 13.)

1. *Preliminary.*—In the autumn of last year a hospitable invitation from the Mayor and Corporation of Southport to occupy some site in or near the town was transmitted by Mr. Joseph Baxendell to the Eclipse Committee, who asked Professor Turner to organize an expedition in response. Ultimately the expedition was made a joint one of the University and Radcliffe Observatories at Oxford, the personnel consisting of Professor Turner from the former, and Dr. Knox-Shaw and Mr. Barrett from the latter observatory, with much kind help on the day of the eclipse as mentioned below.

On a preliminary visit to Southport, Jan. 19–21 (during the absence of Dr. Knox-Shaw in Egypt), Professor Turner had the kind assistance of Mr. C. R. Davidson of the Royal Observatory, Greenwich, who also materially aided the expedition with advice on several subsequent occasions.

The three members of the expedition arrived at Southport on June 22, and were housed by the Mayor and Corporation in or near the Prince of Wales Hotel, about a mile and a half from King George V. Boys' School, which had been selected as the observing site.

A cycle-shed in the school grounds was quickly adapted as a very convenient shelter for the instruments, and a dark-room in the school buildings was put at the disposal of the expedition.

The only serious difficulties encountered arose from the weather, which was atrocious. One or two passing glimpses of the sun enabled adjustments to be made, so that on the morning of the eclipse all was in readiness, but there was no adequate opportunity of testing the driving clocks.

2. *Instruments.*—(a) *Cœlostat.* One of the 16-inch cœlostats was purchased from the Eclipse Committee (according to Professor Newall's suggestion) by the help of a timely grant from the Lord Leigh Fund, and sent to Messrs. Grubb, Parsons & Co. for overhauling and reconstruction along with other similar instruments. To it was pointed the astrographic 13-inch object-glass of the University Observatory, mounted in the temporary tube, made of gas-pipes surrounded by black cloth and Willesden canvas, which had been used in Egypt in 1905. The horizontal position was adopted for the tube, which was mounted on wooden trestles made by the borough Office of Works. The cœlostat

was placed upon its own wooden box: a filling of sand had been intended, but under the circumstances it was found more convenient to fill with coal, with a preliminary newspaper lining.

(b) *Polariscopes.* To determine the polarisation of the corona Professor Turner has on former occasions used, first, Iceland spar, and secondly, reflection from one surface of a glass prism placed before the object-glass. These arrangements only allow of small instruments, and on the present occasion it was determined to try a simple method which allows the use of larger lenses, namely, to place a piece of ordinary plate-glass, blackened on the back, just within the focus at the polarising angle. Mr. Davidson kindly verified that blackening the plate on the back effectively destroyed the second reflection. The lenses used were two halves of "the Abney Lens" (used on several previous eclipse expeditions) belonging to the Royal Astronomical Society. The lenses are of 4-inch aperture, and 5-foot focal length, and were mounted in tubes made of thin 5-ply wood, with oblique extensions for the plate-holders, the polarising plates being held in grooves about 8 inches within the focus. The cameras were screwed together and mounted on an equatorial mounting lent by the Royal Astronomical Society, placed on a wooden stand belonging to the Radcliffe Observatory (which still retains the label indicating its former use by Manuel Johnson).

The whole instrument stood on the ground outside the shed, and was steadied by large paving stones supplied locally. A photograph of it, taken by Mr. R. H. Greswell of Southport (to whom the expedition is indebted for help on several occasions) is reproduced (Plate 13).

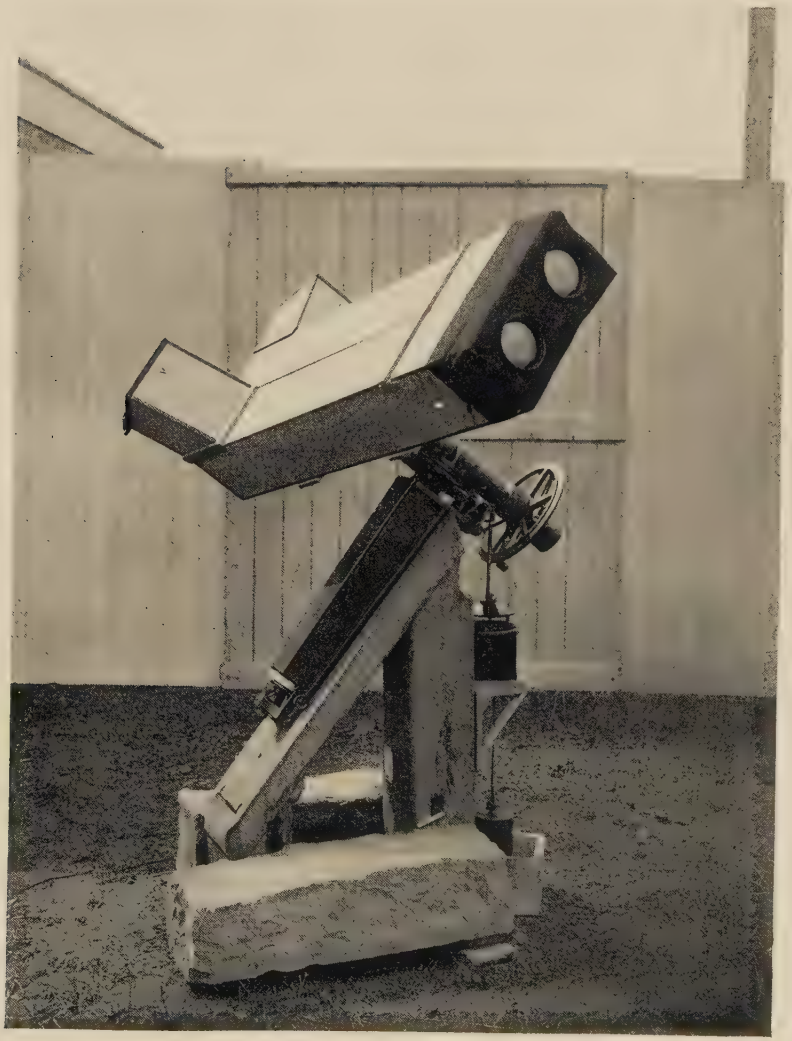
(c) *Focussing.* In default of any fine weather focussing of all three instruments was effected in the dark-room (or adjoining corridor) by artificial light, scratches being made on a blackened half-plate to serve as the origin of the transmitted beam, and the cœlostat mirror being used to reflect the rays back through the object-glass to the other half-plate in the familiar way. In the case of the polariscopic cameras the transmitted beam was considerably weakened by the two reflections from plain glass surfaces, and a strong electric light was therefore necessary.

The rays were found to focus sharply, in spite of the fact that the reflectors were only of commercial plate-glass, and not optically true. This may be considered a satisfactory test of the apparatus for the purpose intended.

(d) *Exposures and Standard Wedges.* It was determined to give the polariscopic pictures a single exposure over practically the whole time of totality, and the astrographic pictures two exposures of 2 seconds and 5 seconds. With the weather of the actual eclipse morning the 5-second exposure might with advantage have been longer, but it was decided to carry out the programme without alteration.

Ilford Zenith plates were used in the polariscopic cameras, and Special Rapid plates in the astrographic telescope.

Standard wedges were impressed on all the plates in the Clarendon Laboratory, Oxford, under the kind supervision of Mr. I. O. Griffith and Dr. G. M. B. Dobson.



Oxford Eclipse Expedition, 1927.

The Polariscope.

3. *Time Signals, Rehearsals, etc.*—On application to the Astronomer Royal, a chronometer was lent by the Admiralty.

The King George V. School was already in possession of a wireless receiving apparatus, and a loud-speaker was set up for the occasion, and manipulated by Mr. Ralph Thompson (one of the masters), so that the signals sent by the B.B.C. could be clearly heard; but at the rehearsals, which were conducted as usual, it was found desirable to have the seconds counted aloud from the word "go" (as called by Professor Turner), and these were counted on the day of the eclipse by Mr. C. Woodham.

As the naming of the seconds by the loud-speaker was not audible, Mr. D. C. Leech, who was standing by at the chronometer in case of failure of the wireless signals, took up the count.

The assistance available being practically unlimited, it was easy to have the times of the exposures checked by several observers, and the services in this connection of the following gentlemen are acknowledged: Messrs. H. L. Eley, Kingsley Laurent, G. Pearson, G. Shaffer, A. G. Lessiter, and J. Irvin. In addition, Messrs. J. F. Cunningham and J. L. Paisley handed plate-holders to and from Professor Turner at the astrographic telescope, exposures at the object-glass being made by Mrs. Turner; while Dr. Knox-Shaw and Mr. Barrett handled the polariscopic plates, the exposure at the object-glass being made by Mr. E. B. Knobel.

4. *The Day of the Eclipse.*—After the long spell of almost continuously cloudy weather, it was a glad surprise to see the sun on June 29 soon after sunrise, though only through thin cloud which persisted throughout. Heavier clouds obscured him at intervals, so much so that the crescent form was not discernible to the naked eye; and there was considerable cloud during totality, but fortunately the corona was visible through the clouds, and was seen by the numerous visitors to Southport, estimated at 250,000.

The programme was carried through as arranged. Many of the usual accompaniments of an eclipse were obscured or lost, owing to the poor conditions. Mr. Barrett and Mr. J. H. Reynolds (who joined the expedition on June 28) both tried unsuccessfully to observe the flash-spectrum with direct-vision spectroscopes. The boys of the school had prepared a white wall for observation of the shadow bands, but had nothing to report.

Baily's Beads were seen by Mr. J. Edwards, using a small telescope, and by Arthur Laws, one of the hundred boys brought by the enterprise of the *Daily News*; and some of the bright prominences by various observers. Five minutes after totality it was raining.

Had the weather been generally good the whole spectacle might fairly have been regarded as a disappointment; but under the actual circumstances it may fairly be called a joyful surprise.

5. *Development of Plates.*—Three of the plates were developed in the school dark-room, namely, the 2-second exposure with the astrographic telescope and both the polariscopic plates: the results, of course, showed images diffused, and in part obscured, by the cloud, but were good enough to suggest deferring development of the 5-second exposure

until a standard wedge had been put upon it at Oxford ; for owing to a change in the selection of plates this had not been done. On development later this exposure showed some curious signs of drift, from which the 2-second exposure was free : as already stated, there had not been opportunity to test the short-period accuracy of the driving mechanism, but it is difficult to suggest a satisfactory explanation of the appearance observed.

Owing to the clouds it seems scarcely worth while to make elaborate measures of the photometric results, but the polariscopic pictures show even to casual inspection the difference between the two components, and it is inferred that the method is well worth a trial at future eclipses.

6. *Acknowledgments.*—It would be difficult to say too much in recognition of the kindly help received from the Mayor and Corporation of Southport ; from Mr. T. E. Wolstenholme (Publicity and Attractions Manager) ; from the Director of Works and those whom he sent to help us ; from Mr. G. A. Millward, Head Master of King George V. Boys' School, and his staff ; and from the police, who made arrangements for the safeguarding of our instruments during the night, and for our being quite undisturbed on the critical occasion.

A word may be added in appreciation of the wonderful way in which the stress arising from the sudden influx of immense crowds was met by everyone in Southport, though this is perhaps scarcely germane to the account of a scientific expedition.

The Total Solar Eclipse of 1927 *June* 29: *Report of the Norman Lockyer Observatory Expedition.* By William J. S. Lockyer, M.A., Ph.D., Major (late R.A.F.). (Plates 14, 15.)

The eclipse party from the Norman Lockyer Observatory consisted of Lt.-Col. Sir Francis K. McClean, Captain W. N. McClean, and myself. The site for the eclipse camp was selected early in March.

Its position (Lat. 54° 25′·8, Long. 1° 43′ W.) lay on the eastward and adjoining side of the main road connecting Richmond (Yorkshire) with Gilling village and distant one mile to the north-east from the market-place of the former town. It was situated on the Marquess of Zetland's estate and called the " Olliver Ducket Mound," and he very kindly gave permission for the Observatory's party to take up their position there. The site was situated on a 600-foot contour line, and looking away from it towards the north through the east and to the south-east the ground fell away sharply at first and gradually afterwards.

On the eastward side of the site was a massive historic " Ducket " or look-out tower. This tower was made considerable use of, not only for storing packing-cases under shelter on the ground floor, but for the erection of instruments on the eastern side of the upper storey in the open. One end of the wireless aerial was also attached to the top of the tower.

The low altitude of the sun, namely 12° 40′, combined with the brevity of totality, 24 seconds, at the Olliver Ducket Mound controlled to a great extent the choice of the instrumental equipment and the programme of work to be attempted. Had totality been of greater duration, more use would have been made of equatorial mountings and siderostats.

The actual programme decided upon was to secure large- and small-scale photographs of the corona, chromosphere, and prominences, and also a small-scale photograph of the spectrum of the corona. Time determinations of the contacts, using the broadcast time-signals, were also to be attempted. At Sidmouth the large partial phase was to be utilised to secure photographs of the spectrum of the chromosphere with a large dispersion instrument erected specially in the grounds.

During the whole of our stay the weather was most unsatisfactory, and there were only four fine days, namely, the 19th, 20th, 23rd, and 28th. On the 21st there was a strong gale, and the other days were chiefly wet.

On the early morning of eclipse day (29th) the sky was very cloudy, but the sun was visible at $3^h\ 35^m$ G.M.T. just above the horizon. At $4^h\ 10^m$ the clouds seemed to be breaking up, and blue sky was seen in the direction from which the clouds were drifting, namely, S.E. At $4^h\ 35^m$ the valley mists began to rise as if they were about to begin to dissipate, and they reached very nearly to our elevation of 600 feet. At $4^h\ 50^m$ the prospect of seeing totality improved, and the crescent sun was seen at $5^h\ 0^m$ for a few minutes in a perfectly clear gap. At $5^h\ 7^m$ clouds again completely obliterated the sun, and at $5^h\ 15^m$ the conditions looked entirely hopeless, and continued so until well after half of the second series of partial phases had elapsed, and even then for only a few minutes was the sun seen.

In accordance with the instrumental programme and the megaphone time-signals the whole routine work of the camp was gone through at the total phase, but, of course, with no successful results.

The instruments erected on the site formed themselves naturally into three groups, namely, those that were brought by each of the three members of the expedition.

Thus Sir Francis McClean's group of instruments consisted of the 6-inch Steward equatorial and a 3-inch coronagraph, both of which he operated himself, and a 6-inch aperture of 31·5-foot focal-length coronagraph, which he put in charge of Captain Leeston Smith (see Plate 14).

The second group consisted of a Ross-Williamson telephoto camera of 25-foot equivalent focal length, which Captain McClean operated with the assistance of Mr. Hunter, and two Beck instruments of focal lengths of 3·4 and 4 feet, worked by Mrs. W. N. and Miss McClean and Mr. J. McClean respectively.

While the above instruments were situated on the ground, my group was placed on the upper floor of the "Ducket" on the eastern side of the tower (see Plate 15). The Thorpe grating spectrograph, fitted with a Zeiss triplet aeroplane lens, and a Dallmeyer rectilinear coronagraph, both instruments being carried on a 12-inch siderostat mounting, were operated by me, and the Zeiss triplet and Aldis triplet

coronagraphs were in charge of Mrs. W. J. S. Lockyer and Mr. F. McClean respectively.

A special position was selected on the western portion of the ground for the exposure of a film during the whole time of totality to show the eastern aspect of the camp, including the "Ducket" and the eclipsed sun. Miss Lockyer was in charge of the instrument that was employed.

The composition of these groups is contained in the following table (Table I.), which sums up details concerning all the instruments, plates used, exposures, operators, etc.

TABLE I.

Instrument.	Aperture.	Focal Length.	Plates Exposed.	Brand of Plates.	Exposure.	Object.	Operator.
	In.	Ft.			Sec.		
Cooke (Moving Plate).	6	31·5	1	Ilford S.R. Pan.	20	Corona.	Capt. Leeston Smith.
Steward (Equatorial).	6	4	1	,,	20	,,	Sir Francis McClean.
..	3	4	1	,,	2	,,	,,
Ross-Williamson (Telephoto).	2·5	25	20	Excelsis Film (Imperial Dry Plate Co.).	$\frac{1}{10}$	Chromosphere Prominences.	Capt. W. N. McClean and Mr. Hunter.
Beck.	3	3·4	2	Imperial S.R.	1–2	Corona.	J. McClean.
Beck (Telephoto).	0·9	4	2	Ilford Ord.	$\frac{1}{100}$: 1	Baily's Beads Prominences.	Mrs. W. N. McClean and Miss McClean.
Zeiss Triplet	4	1·6	1	Ilford Iso Zenith.	20	Corona Spec.	Dr. W. J. S. Lockyer.
Thorpe Grating (Equatorial).	..	..	1	,, Empress.	20	Corona.	,,
Dallmeyer (Rectilinear).	3·4	1·2	1	,, Ordinary.	20	Corona.	,,
Zeiss Triplet.	4	1·6	2	,, Iso Zenith.	2 : 3	,,	Mrs. W. J. S. Lockyer.
Aldis Triplet.	4	1·7	2	,, ,, ,,	3 : 2	,,	F. McClean.
Kodak.	..	..	..	Kodak Film.	20	Landscape.	Miss Lockyer.

Not having obtained any photographic results, no useful purpose would be gained by describing the equipment in greater detail, but there are some points of interest concerning the chief instruments which may be found helpful on future eclipse expeditions. These are described in subsequent sections.

The eclipse party wish to express to the following their hearty thanks for valuable assistance rendered :—

The Marquess of Zetland, for the use of the "Olliver Ducket Mound"; Captain Nelson Rooke, agent to the Marquess, for giving every facility to ensure the success of the expedition; Messrs. J. H. Richard-

son and F. Stretch, the stationmasters at Richmond and Sidmouth respectively, for personally supervising the handling of the packing-cases on their arrival at and departure from Richmond and Sidmouth.

The 31·5-foot Coronagraph.

The chief points of interest of this instrument were the methods of construction and erection of the tube. The instrument consisted of a 6-inch Cooke photo-visual objective of 31·5 feet focal length. The tube (Plate 14) was mounted so as to point directly to the calculated position of the sun at mid-eclipse. It consisted of four strong wooden frames with graduated rectangular openings connected by hollow steel rods, these rods, threaded at each end, passing through the wood frames and being capable of being adjusted and locked to the frames by duplicate bolts and washers. The frames rested on wood supports constructed to give them the correct angle of elevation and inclination to the horizontal. Each of these wooden supports rested on main wooden trestles fixed in the ground at heights suitable to the contour of the ground. The tube was covered with a double thickness of light-tight material and waterproof fabric.

The object-glass was mounted in a heavy cast-iron frame, which in its turn was clamped to a wooden frame. This was fixed at the east end in front of the main tube on a separate foundation to avoid any vibration of the main tube. It was only attached to the tube by a flexible, double, light-tight fabric.

The main tube being in a fixed position it was necessary to have some arrangement by which the dark slide could be moved to correspond to the movement of the solar image.

The dark-slide holder was mounted on a wooden frame similar to the tube frames, and rested on a short trestle fixed in the ground at the west end of the main tube. It was quite independent of the tube, being connected only by a flexible, double, light-tight fabric. The dark-slide holder had an aperture of 12×24 inches, and carried a dark slide holding a plate 12 × 12 inches for obtaining one exposure on the corona of 20 seconds' duration. This dark slide was capable of moving smoothly inside the dark-slide carrier. It was so designed that it was pulled in the direction of the movement of the solar image by means of a weight, and the speed was controlled by a gramophone clock. The desired speed was approximately 1·5 inches per minute, which gave a run of 8 minutes, during which the sun could be followed.

The Ross-Williamson Telephoto Camera.

This instrument consisted of a German aeroplane camera in combination with a Ross lens of 2·5 inches aperture. In front of the aeroplane lens was fitted an aluminium extension tube 4 feet long, carrying at its upper end a 2·5-inch aperture lens with filter case and stops attached. The whole combination gave a virtual focal length of 25 feet and a solar image of about 3 inches. The overall length of the instrument was about 8 feet 6 inches.

The instrument was fitted with a film roll-holder for a $6\frac{3}{4} \times 4\frac{3}{4}$-inch picture geared to shutter and operated by turning a handle, one revolution of the handle changing the film and setting the shutter. The maximum capacity of the roll-holder was 100 exposures. There was also attached a Ross monocular finder (× 9) with fine adjustment for collimation and cross-hairs.

The camera was adapted to a cinematograph projector stand, and both vertical (inclination) and azimuth screw adjustments were available. As sufficient inclination could not be secured with the vertical adjustment, the front support was raised by wooden blocks, both supports resting on concrete foundations.

The whole instrument was housed in a corrugated iron shelter, as illustrated in the right-hand top corner of Plate 14.

The Thorpe Grating Zeiss Spectrograph.

The novelty of this instrument was not so much the instrument itself, for I have used similarly constructed instruments at previous eclipses, as the method of mounting it.

The spectrograph was composed of a Zeiss triplet aeroplane lens, in front of which was mounted in a wooden holder a Thorpe transparent grating of ruled surface 3 × 2 inches. These were fitted in a wooden tube of square section that slid into one side of an oblong box with scale attached for focussing purposes. The opposite end of this box was arranged to carry a plate-holder for a $12 \times 4\frac{3}{4}$ plate. Actually two plates were inserted, namely, one a slow plate of 5 × 4 inches for recording the direct image of the corona, and the other a very rapid plate of 7·9 × 4·8 inches for the coronal spectrum in the first order. Special diaphragms were inserted in the box to eliminate fogging by reflection from the other orders of the grating.

The base of this box was strongly hinged at the plate end to another wooden base of the same dimensions, and side supports with clamping screws were so fixed that these boards could be clamped at any inclination to one another.

As it was not considered desirable at this eclipse to make use of a 12-inch siderostat, the mounting of this instrument was stripped of the mirror fork and cell and other unnecessary parts, and the mounting utilised to carry the above spectrograph, as illustrated in Plate 15, figs. 1 and 2.

To the upper end of the polar axis a strong, circular, wooden disc was firmly fixed to the driving circle, and on this was screwed firmly the hinged wooden base of the spectrograph.

In this way one obtained a mounting adjustable for latitude and azimuth, and clock driven. It was only necessary to adjust the angle between the boards to the declination of the sun and the instrument was complete for the eclipse. To make further use of this mounting another box camera, carrying a Dallmeyer rectilinear lens of 3·4 inches aperture, was screwed to the top of the grating camera. The whole arrangement was brought into good balance by fixing the base board of the spectrograph unsymmetrically on the wooden disc.

FIG. 1

FIG 2

The instrument was erected on the upper platform of the " Ducket," and the clock driving-cord and weights were led to the outside wall by a system of pulleys, thus securing an available 12-foot fall (see Plate 15, fig. 1).

The whole arrangement worked exceedingly well, and suggested that probably quite a cheap form of mounting after this principle might be usefully adopted for instruments of moderate dimensions.

The Time-Signals.

From $5^h\ 0^m$ to $5^h\ 20^m$ G.M.T. the megaphone calls at five-minute intervals were taken from the wireless time-signals. The time and calls of the minutes after $5^h\ 20^m$ were taken from a stop-watch which was correct at that signal; thus it was only necessary to rely on the accuracy of the watch for five minutes only. Commencing at $5^h\ 24^m\ 10^s$ single seconds were called, the beats being timed from the bell of the eclipse pendulum clock, which pendulum was started four minutes before the calculated time of the commencement of totality and adjusted to beat seconds in time with the B.B.C. signals.

Time rehearsals were first commenced on the 27th, and several were held during the day. On the 28th full rehearsals took place at $5^h\ 0^m$ a.m., $9^h\ 30^m$ a.m., and $3^h\ 30^m$ p.m.

It is pleasing to record that all the time arrangements went absolutely according to plan on eclipse day, and this was due to the very efficient way in which Major Chapman and Mr. F. McKay, who assisted him, carried out the programme.

The Sidmouth Preparations and Results.

To take advantage of the large maximum phase of the eclipse (0·97) visible at the Norman Lockyer Observatory, preparations were made for photographing the spectra of the chromosphere and photosphere at the sun's limb with large dispersion, and also for securing a series of photographs of the partial phases themselves.

For the purpose of the former the laboratory Littrow spectroscope (Hilger) of 2·5 inches aperture and 8 feet focal length, giving a dispersion of 27 cm. between Hβ and Hδ, was erected in the grounds. A telescope with a $3\frac{3}{4}$-inch objective and of 4 feet 6 inches focal length was employed for throwing an enlarged image of the sun on the slit, and this was fed by a 12-inch siderostat.

Only a portion of the spectrum could be photographed at any one time, and only two plate-holders were available, each holding a plate 10 × 2 inches, on which four exposures could be made. The plate-holder could be moved vertically by rack and pinion to secure the four exposures.

The programme was to take twenty-four photographs in three series of eight exposures each, changing the plate in each holder after every eighth exposure. The necessary alteration in the adjustments of the prisms, focus and swing back, for the red and violet regions of the spectrum were made alternately after the fourth, twelfth, and twentieth exposures.

For the photography of the partial phases the 10-inch McClean telescope was used. The aperture of the object-glass was reduced to 1·1 inches by means of a wooden diaphragm placed in front of the lens, and on this a very fast-moving shutter with a slit width of 0·2 inch was mounted.

The weather previous to and on eclipse day seems to have been as unfavourable as it was in Yorkshire. No exposures at all could be made with the Littrow spectroscope, and only two, namely, at $4^h\ 30^m$ and $4^h\ 40^m$ a.m. with the McClean 10-inch refractor, and neither of these are free from cloud.

Mr. D. L. Edwards was responsible for the erection of the instruments, being assisted by Mr. H. W. P. Richards, a research student at the Observatory, and by Mr. Boot, the attendant of the Observatory.

Description of Plates.

Plate 14. The 31·5-foot coronagraph, together with the 6-inch Steward equatorial and the 3-inch coronagraphs. Reproduced by kind permission of the *North Mail and Newcastle Chronicle.*

Plate 15, fig. 1. The Thorpe grating Zeiss spectrograph and the Dallmeyer coronagraph on the mounting of the 12-inch siderostat, and the Zeiss and Aldis triplet coronagraphs on fixed bases, as erected on the "Ducket."

Plate 15, fig. 2. The above-named spectrograph to show the method of mounting.

Total Solar Eclipse, 1927 *June* 29: *Report of Dr. R. L. Waterfield's Expedition.* (Plate 16.)

Owing to the kindness of the Rev. C. D. P. Davies and the Headmaster of Giggleswick School, I was allowed to set up my instruments in the eclipse camp on a part of the school grounds.

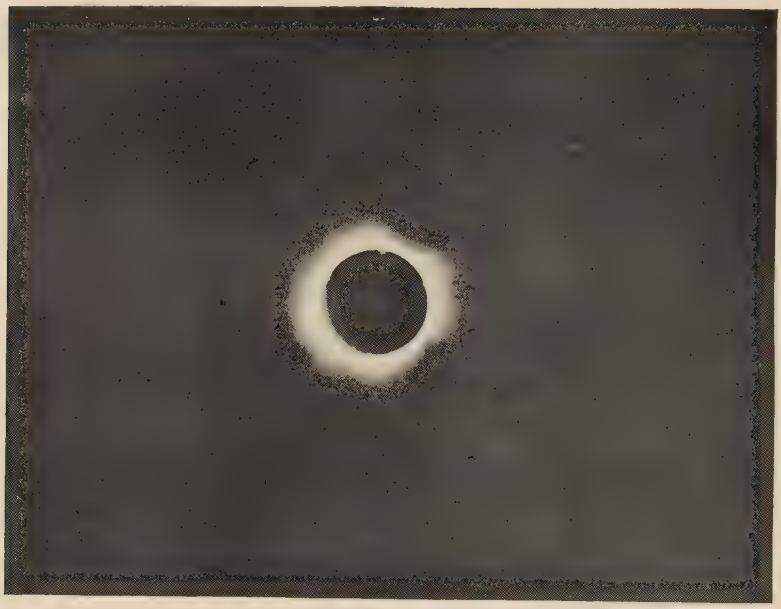
My own expedition consisted of Mr. W. E. B. Lloyd, the Very Rev. the Dean of Hereford, and myself. The instruments comprised three coronagraphs of varying focal lengths, a prismatic camera, a slitless visual spectroscope and a small telescope. Mr. Lloyd used the telescope and manipulated the two smaller coronagraphs. I myself observed the flash spectrum and worked the prismatic camera and large coronagraph. The Dean of Hereford assisted generally.

The programme arranged was (1) the photography of the first flash at second contact with a red sensitive plate—an Empress (Ilford) plate bathed the night before by Mr. Melotte with dicyanin—and of the second flash at third contact with a supersensitized panchromatic plate of speed 1250; and (2) three direct photographs of the corona to be taken one with each of the coronagraphs.

The prismatic camera consisted of a prism with replica grating on one surface (by Hilger) placed in front of an ordinary spectacle lens of 24-inch focal-length. By tilting a flat plate good focus was obtained on test plates from the middle of the green to well beyond the visible red. Owing unfortunately to a foolish mistake in the working of the

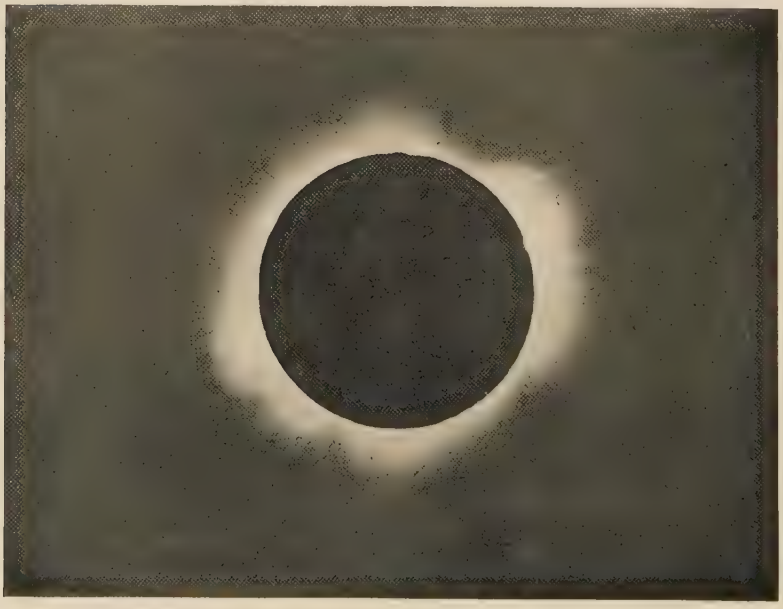
N

(A)



E W

(B)



S

Solar Corona, 1927 June 29. R. L. Waterfield.

(A) 3-in. doublet, f.l. 24 in. Exp. 1·5 sec.
(B) 4-in. refractor, f.l. 60 in. Exp. 0·75 sec.

shutter, the first—red sensitive—plate was spoilt, while the second—panchromatic—plate only got about $\frac{1}{4}$-second exposure, and thus showed only the two crescents of Hα and the yellow Helium line.

The large coronagraph, worked by myself, had a 4-inch Wray visual objective with a focal length of 60 inches. A few inches in front of the plate a "Beta" (Ilford) gelatine filter with exposure factor × 3 was used. This filter, by cutting out the two extreme ends of the spectrum, approximately corrected the lens photographically, and helped to reduce the effect of scattered sky-light. The exposure given was $\frac{3}{4}$ second and a supersensitized panchromatic plate, speed 1250, was used. The photograph (here reproduced, B) shows on the original a considerable amount of detail in the prominences, including three detached portions of a prominence on the east limb; a small complete coronal arch near the south pole; a curious "lumpy," or mottled, appearance in the outer corona on the east; and a number of straight narrow rays and broader curved streamers. The maximum extension, which is to the west, is just less than half the sun's diameter. Most of the detail and some of the extension is of course lost in the reproduction.

The next coronagraph, operated by Mr. Lloyd, had a 3-inch doublet by Beck of 24 inches focus. A "Delta" (Ilford) filter with exposure factor × 4 was placed a few inches in front of the supersensitized panchromatic plate of speed 1250. The purpose of this filter was also to diminish the effect of sky-scattering. The exposure given was $1\frac{1}{2}$ second. This photograph (reproduced here, A) shows on the original rather more extension—just over half a solar diameter to the west—but much less detail in the inner corona than the photograph with the 60-inch coronagraph. It does, however, show the largest prominences, and gives a good representation of the rays and streamers. But the inner corona, through over-exposure, intrudes obviously upon the eastern limb; and there is halation corresponding with this part of the corona in the form of a brightness near the centre of the moon's disc and of a faint arc of light lying just beyond the limit of the corona on the east.

The smallest coronagraph, also worked by Mr. Lloyd, had a small Dallmeyer telephoto lens of 16 inches focus. The same plate as in the other cameras was used, but no filter was employed. The exposure given was $2\frac{1}{2}$ seconds. The coronal extension shown—the picture is *not* reproduced here—is about the same as that got with the Wray lens. But this picture shows, far better than the other two, the vast contrast in brilliance between the inner 2′–3′ rim of corona and the rest of the corona.

In conclusion I should like to express my thanks to the Rev. C. D. P. Davies for his invitation for us to join his party; to Mr. Melotte for bathing my red-sensitive plates; to Mr. Hargreaves for his advice concerning the use of filters and rapid plates; and to the Imperial Dry Plate Company, who specially sensitized the plates and presented them to me both for the preliminary tests and for the eclipse itself. Also I should like to express my gratitude for the kind hospitality and much willing assistance which I and my party received from the staff and boys of Giggleswick School.

The Total Solar Eclipse of 1927 *June* 29: *Report on an Expedition from the Solar Physics Observatory, Cambridge, to Aal* (*Hallingdal*), *Norway.* By H. F. Newall, J. A. Carroll, W. M. Smart, C. P. Butler. (Plate 17.)

The Solar Physics Committee having sanctioned the sending of an expedition from the Solar Physics Observatory, Cambridge, to observe the total eclipse of the sun on 1927 June 29, it was arranged with the Joint Permanent Eclipse Committee of the Royal Society and the Royal Astronomical Society that the party should go to Norway, where the eclipse would occur at altitudes considerably higher than at any site in England.

From correspondence with Professor J. Fr. Schroeter, it had been made clear that a kind welcome would be given to such an expedition by the Norwegian authorities, who had already decided that instruments required for the observations should be admitted into Norway without duty or examination. Professor Schroeter's untimely death on 1927 April 27 was a matter of deep regret in a wide circle, not least to those who had experience of his courteous and prompt response to their enquiries relating to the eclipse.

The choice of an observing station was decided after a visit made early in 1926 September by Professor Newall and Dr. Carroll to Aal, in Hallingdal, a place which lies on the Bergen-Oslo railway and is close to the line of central eclipse. Professor V. Bjerknes was kind enough to meet them at Aal, and to assist in the search for a suitable site.

A site was found at Aal in the grounds of the Sundre Hotel, in all respects so convenient that it seemed unnecessary to make further search at Ringebu or Fagernes. The expedition was assured of willing assistance from the proprietor of the hotel and from the local authorities, and observations on the site rendered it possible to make an oriented plan of the ground and so to provide for a suitable placing of instruments. This preliminary visit gave a feeling of certitude and contentment, which is not always present in the mind of the leader of an eclipse expedition to a foreign country, and served to save the time usually spent in search for a site and in planning the arrangement of the eclipse camp after arrival on the scene of operations.

Professor Schroeter gave a cordial assent to the choice of Aal as observing station, and announced that Dr. Rosseland was arranging to occupy a site at Fagernes in the neighbouring valley Valdres, together with Professor S. A. Mitchell of Leander McCormick Observatory, U.S.A. Special facilities were assured by the helpful action of H.M. Foreign Office on behalf of the expedition.

The party, consisting of Professor and Mrs. Newall, Dr. Carroll, Dr. W. M. Smart, Mr. C. P. Butler, and Mr. L. J. Stanley, travelled out to Aal, via Newcastle and Bergen, leaving Newcastle on 1927 June 4; and Professor and Mrs. Bryant, of Middlebury, Vermont, U.S.A., joined them at Newcastle, he having very kindly volunteered assistance in the preparations at Cambridge and in the operations at Aal. Mr. F. J. M. Stratton arrived at Aal on June 23, and Professor

E. A. Milne on June 27, they having kindly volunteered assistance in the eclipse observations.

The twenty-five cases of instruments and nine bales of tenting and huts arrived on the site on June 8, and the positions of the instruments were staked out by the evening of June 9. The erection of the instruments and the wooden structures needed for their support proceeded apace in very inclement weather, the season being declared by local authorities to be about a month later than any in the previous twenty-five years. Nevertheless, hopes were raised in the first week by the occurrence of fine conditions of the sky at 6.30 a.m. (about the time of day at which the eclipse would be total) on four mornings out of seven, only to be followed in the week before the 29th by a crescendo of despondency at a succession of seven mornings when the conditions at that hour were hopelessly bad. Professor Hesselberg kindly sent the daily meteorological reports and forecasts from Oslo, but little comfort could be derived from them.

The first rehearsals of the eclipse operations took place on Saturday 25th with the instruments nearly completely adjusted by various devices necessitated by the fitfulness and short durations of visibility of the sun. Mr. Stanley counted seconds to the beat of a metronome; Dr. Smart, who was in charge of the 20-foot coronagraph, called out the signals "crescent" and "go" with judicious variations in the supposed occurrence of those well-known events. The third and final set of rehearsals was held on the evening of the 28th with all the instruments completely adjusted but for the final touches, for which fifteen minutes of sunshine on the morning of the 29th would have been sufficient.

The morning of the 29th was completely overcast from 4 a.m. onwards, and all sight of the eclipsed sun was entirely frustrated by thick cloud. Before midday the large majority of the optical parts had been taken out of the instruments, and by the evening of the 30th the packing up was completed with a speed which was largely due to the efficient help of Mr. Stratton and Professor Milne. The cases arrived in Cambridge by the middle of July.

At this point this report might well stop; but it is thought that a brief description of the observations aimed at may be useful for another eclipse or for other observers.

The programme of observations may be most easily described by reference to the three centres at which the various observations were to be collected, namely, the equipment of Professor Newall and Dr. Smart, the equipment of Dr. Carroll and Mr. Stratton, and the equipment of Mr. Butler, which served also to supply light for the interferometer work arranged by Dr. Carroll and Professor Bryant.

In Professor Newall's equipment there was the 16-inch silver-on-glass cœlostat, recently purchased from the Joint Permanent Eclipse Committee and provided by Sir Howard Grubb, Parsons & Co. with a new driving sector and remodelled clockwork. The alterations have proved very satisfactory in every way. A second cœlostat, the 9-inch plane speculum mirror of which had been kindly lent by the Astronomer Royal, was connected with the larger cœlostat by a simple link work,

so that one clock served for the two mirrors. Plate 17 shows the arrangement clearly enough to require no further explanation.

The 16-inch mirror gave a reflected beam, which supplied light to four instruments pointed horizontally at the cœlostat in the azimuth of sunset :

(*a*) A polarising camera of focal length 66·8 inches, with a large Nicol prism in front, transmitting a 2-inch beam A/F=1/33·4 and giving an image of the sun, 0·62 inch in diameter on a plate $6\frac{1}{4} \times 6\frac{1}{4}$ inches. With it two photographs on extra-rapid plates were to be taken with exposures of 10 seconds, with the plane of polarisation (1) parallel, and (2) perpendicular to the sun's axis of rotation. A Savart polariscope was provided for a determination of the plane of polarisation of the sky round the eclipsed sun.

(*b*) A photoheliographic camera giving a solar image 1·5 inches diameter, unpolarised, on a plate $6\frac{1}{4} \times 6\frac{1}{4}$ inches. With it two photographs were to be taken, one on a rapid plate for comparison with the polarised images, the other on a slow plate, with exposures of 10 seconds each, taken simultaneously with the polarised images.

(*c*) A 10-inch mirror, diverting the beam into a coronagraph, with a photovisual lens of diameter 6 inches and focal length 20 feet. This instrument was in the charge of Dr. Smart.

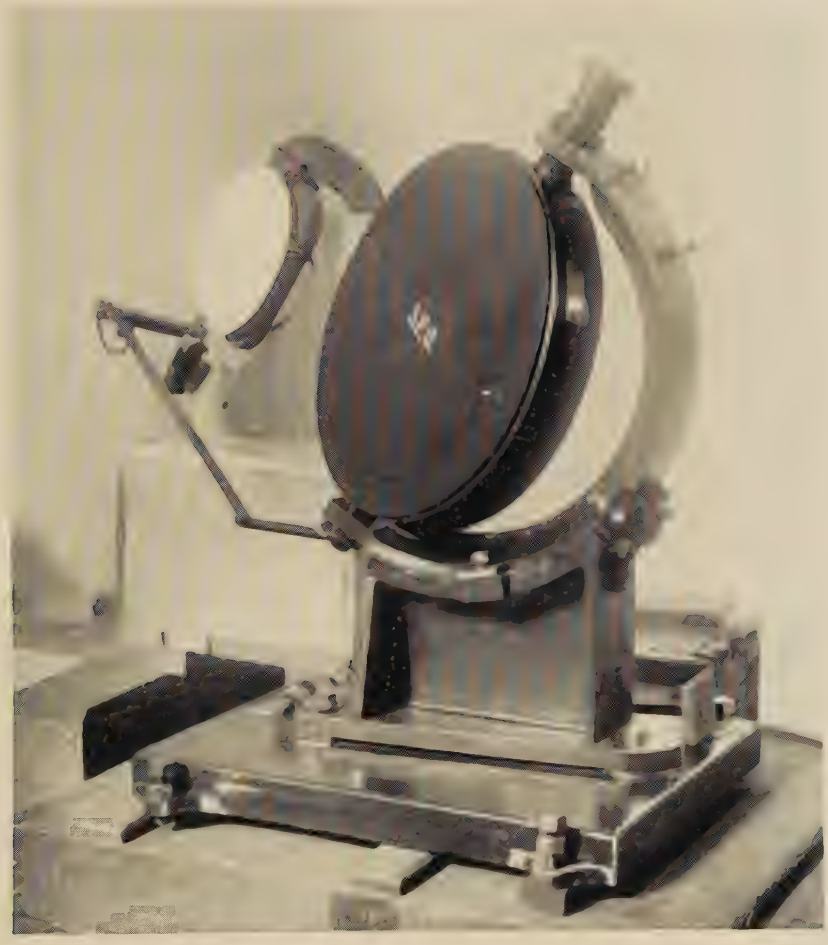
(*d*) A camera of focal length 11 inches, for long extensions of corona.

The 9-inch speculum mirror gave a horizontal reflected beam which supplied light to the 9-inch Herschel speculum mirror, very kindly lent by Dr. W. H. Steavenson.

(*e*) This gave a 1·1-inch image of the sun on the slit of the Hills quartz spectrograph, which was to be used to obtain two exposures of 3 seconds and 15 seconds on the chromospheric layers, near the northern tip of the crescent with the slit placed parallel to that tangent to the sun's limb which made an angle of about 20° with the path of the moon relative to the sun.

This plan of observation of the " flash " spectrum was adopted in order to gain a longer exposure for photometric purposes than would have been possible had the slit been placed tangential to the sun's limb at the point of second contact. The plan was adopted by reason of the success of the observation of a partial eclipse of magnitude 0·91 in 1912, when Professor Newall photographed the chromospheric spectrum and Professor A. Fowler observed it visually. In the present eclipse, the effective " magnitude " of the eclipse at the moment of exposure would have been 0·995, and it was expected that in such conditions the telluric scattering of photospheric light would be too small to complicate the observations, since exposures were to be made only when the tip of the diminishing crescent had passed away from what may be called the point of tangency of the slit.

In this equipment, as in every other in the camp, Mr. Stanley's assistance was invaluable.



Two cœlostats linked together and driven by one clock.

In Dr. Carroll's equipment there was a second 16-inch cœlostat, kindly lent by the Royal Astronomical Society. It also had been remodelled by Sir Howard Grubb, Parsons & Co., and worked completely satisfactorily.

This instrument was also set to give a horizontal beam in the azimuth of sunset, and supplied light for two instruments :

(*f*) A single-prism spectrograph of low dispersion, for a study of the relative intensities in the chromospheric spectrum of the H and K ($^2S_1 - {}^2P_{1,\,2}$) lines of Ca II and the infra-red diffuse doublet and satellites ($^2P_{1,\,2} - {}^2D_{2,\,3}$) and for photometric measurements of such other lines as fall in the region of the spectrum embraced by the instrument λλ3700–9000.

This instrument was provided with a slit, on which an achromatic image of the sun 22 mm. in diameter was thrown from a concave mirror (silver on glass).

Since the aberrations of such a mirror when its beam is used off the axis are liable to confuse the light from the chromosphere, an axial beam was used by inserting an inclined plane mirror to send the light to the spectrograph. A microscope was arranged for viewing and setting the image, so that no part of the slit was covered by the moon before the end of the exposure. In order to facilitate photometric measurements and to ensure a suitable density of spectral image, a device was introduced for securing simultaneously two spectrograms of the chromosphere having a known ratio of intensities (approximately 10 to 1). This consisted of a plane parallel plate of unsilvered glass about 10 mm. thick placed a few centimetres within the focal plane of the spectrograph camera and inclined at an angle of 45° to the axis of the beam. Whilst most of the light passes through the plate, suffering a small displacement, some of it is reflected at the front face in a direction perpendicular to the original beam and is received on a second photographic plate cut from the same large plate as that which receives the direct image. Undesired images formed by successive reflections at the two faces of the glass plate are masked off by using a plate of appropriate thickness and inserting an opaque diaphragm. Suitable provision for photometric requirements is dealt with below.

The instrument in the eclipse was operated by Dr. Carroll with the assistance of Miss Andersen, a visitor from Oslo in the hotel, to whom the expedition was much indebted not only for this help, but also for the much-appreciated assistance most willingly rendered on the many occasions when the services of an interpreter were required.

(*g*) A slit spectrograph with a 4-inch plane grating (6000 lines per cm. giving a specially bright spectrum in the first order of the infra-red region) and with the quartz collimator and camera of the Hills flint spectrograph ; for an exploratory spectrophotometric investigation, with high resolving power and dispersion, of the infra-red region (λλ7600–9000 Å. U.) of the chromospheric spectrum.

The scale of the spectrum was about 25 Å. U. per mm. and records of the Ca II infra-red lines in the laboratory were very satisfactory. It would have been desirable to employ for this instrument the device adopted for getting simultaneous exposures of different intensities, but Dr. Carroll thought of the scheme only a short time before the expedition set out for Norway, and it was only possible to instal it on the one spectroscope on which it was of greatest importance.

The instrument was mounted close to the spectrograph of low dispersion and was supplied with light from the same cœlostat through a 6-inch object-glass of focal length 7·5 feet, giving an image of diameter 0·83 inch, which was viewed through a microscope. It was operated during the eclipse by Mr. Stratton.

Provision was made for independent fine adjustments of the image of the sun on the slits of the two instruments. The slits were oriented with respect to the sun's image in the same way as in the case of the quartz spectrograph, and exposures of 2 seconds and 20 seconds were to be made.

Plans for Photometric Measurements of the Spectra.—The following are some of the considerations that guided Dr. Carroll in the arrangement of suitable spectrographs and the provision of the requirements for accurate photometry of the spectra.

Since the absolute intensity of the infra-red lines of Ca II is unknown, the most important consideration was to economize light as much as possible to ensure their being recorded. The only clue we have is that they have been photographed by H. D. Curtis (*Pubns. Allegheny Obs.*, vi., No. 6) as very faint lines with plates stained with dicyanin.

An investigation of the sensitiveness of plates made with the new dye neocyanine incorporated in the emulsion (prepared by Kodak Ltd.) and hypersensitised by bathing in ammonia showed them to be very many times more sensitive in the infra-red region around λ8600 than anything previously available. Such plates were accordingly to be used.

It was decided to use spectrographs supplied with slits, in order to avoid the trouble arising in photometric measurements when objective prism cameras are used—troubles that arise from the gradual occultation by the moon of the different parts of the crescent of the chromosphere after " second contact."

For the deduction of the real intensities at various points of the lines in the spectra obtained, it is necessary to know at all wave-lengths the relation between intensity and photographic density. To eliminate the unknown atmospheric absorption, the solar spectrum was to be used for the photometric standard spectrum. To secure a suitable range of density in all parts of the spectrum, two methods of obtaining the sensitivity curve of the plates were provided :

(1) A coarse diffraction grating (with about 60 lines to the inch) to give a series of spectra of reduced sunlight of known intensity ratio.

(2) A neutral-tint wedge and suitable neutral-tint reducing screens, to be used when a uniformly illuminated area of sunlight falls on the slit.

For the low dispersion spectrograph (*g*), whereby the photometric relations between the H and K lines and the infra-red lines of Ca II were to be found, preliminary experiments with a calcium arc in the laboratory were made. They showed that the neocyanine plates, to produce the $^2P-{}^2D$ lines of Ca II of a given density, required an exposure 20 times as long as that required to produce the H and K lines of the same density. If, then, it is assumed that the lines in the chromosphere are somewhere near the same relative strength as they are in the arc or spark, an exposure of about 20 times that usually given for "flash" spectra with such an instrument, of aperture *f*/10, should show the Ca II lines well. To achieve this and still have measurable H and K lines, a suitable colour filter (two K_1 plates) was introduced into the beam to reduce the intensity of H and K about twentyfold, and two exposures were planned—2 seconds and 20 seconds. The former corresponds to rather less than the usual exposure for H and K, and the latter to about 8 or 9 times as much. Bearing in mind the presence of the device for simultaneous double exposures, we see that, were the infra-red lines within the limits $\frac{1}{200}$th and 200 times the intensity assumed, a satisfactory record might be expected.

For the quartz spectrograph Dr. Carroll had prepared a set of quartz screens sputtered with platinum. Dr. W. H. B. Skinner kindly lent his apparatus at the Cavendish Laboratory for making these screens, and lent some screens prepared and carefully calibrated by him.

For the objective-grating camera a slightly different procedure, which is described below, was provided by Dr. Carroll.

In Mr. Butler's equipment, the Hills heliostat (of Foucault pattern) was used to give a 12-inch beam to supply light to two instruments :

(*h*) An objective-grating camera of aperture 4 inches, and focal length 16 feet, to be used with a moving photographic plate behind a diaphragm placed close to the focal plane of the camera, for recording the change in the spectrum whilst the moon covers the chromospheric crescent on the E limb of the sun, and again whilst the moon uncovers the chromospheric crescent on the W limb.

(*i*) An interferometer equipment, which was in the charge of Professor Bryant and will be described in a later paragraph.

The objective camera with moving photographic plate was in the charge of Mr. Butler. After consideration of several alternative plans, the following arrangement was adopted. It will be most easily described in what may seem to be a "backward" sense, inasmuch as for practical reasons it appeared best to provide if possible for a vertical fall for the photographic plate.

In order that the moving plate and its holder should have a vertical fall, the axis of the objective-grating camera must be horizontal and the plane of dispersion should be also horizontal, and consequently the ruled lines on the grating should be vertical.

In order that the dispersion should be normal to the crescents near the time, not only of second contact but also of third contact, the dis-

persion must be parallel to the moon's path relative to the sun. These several conditions could be satisfied by taking a horizontal beam from the siderostat in an azimuth such that the moon's path in the reflected image is horizontal. By a slight alteration in the mounting of the siderostat, the required azimuth, 25° east of the meridian, was arranged. The grating was adjusted to give the required spectrum with a deviation of 30° from the incident beam, so that the camera of the spectrograph pointed in a direction inclined at 55° east of the meridian.

The spectrograph was constructed with a 6-inch plane grating (Anderson), ruled surface 3·45 × 5·2 inches, with 15,000 lines to the inch and a photovisual objective of aperture 4 inches and focal length 16 feet. The camera was arranged for plates 12 × 10 inches and the spectral region selected for observation, λλ3700–4600, extended over nearly 11 inches with a scale of 3·5 Å. U. per mm.

The diameter of the solar image would be about 1·8 inches, and the chromospheric crescents would be correspondingly large, but only such parts as could pass through a long, narrow slit placed close to the focal plane were to be allowed to fall upon the moving plate. Merfield's fine spectra (obtained in Sumatra in 1926 January) gave useful guidance as to the width of slit and the rate of motion of the plate. It was arranged to use a slit width of 1 mm. and a plate speed of 4 mm. per second, which would give a total fall of about 8 inches for the recording of the changes in the chromospheric spectra, both after second contact and before third contact, the fall running continuously throughout the total phase. In order to preserve the sharp focus of the spectrum on the plate which was slightly inclined to the normal position, it was necessary to arrange for shifting the image on the plate between second and third contacts in the direction of dispersion by an amount equal to the diameter of the sun's image.

The fall of the plate was controlled by fitting the dark slide with two V-grooves sliding on a long steel rod, and with a third point-bearing consisting of an ivorine wheel running on a brass strip screwed to the back frame of the camera, the contact of wheel and strip being maintained by a fine steel wire stretched along the frame. The speed of fall of the dark slide was governed by a gramophone motor, lent by Sir G. Lenox Conyngham.

To furnish a time-scale on the photographic plate, an occulting shutter was fitted inside the camera a few inches from the plate and central with the fixed slit. It consisted of a rectangular frame of two parallel steel rods, 12 inches long and $\frac{1}{4}$ inch in diameter, riveted to two short brass bars, 2 inches long, and pivoted between centres. The frame was rotated by gearing from a small phonograph motor. By regulating the speed to one rotation in 2 seconds, one occultation per second was obtained which would give a fine clear line every second along the whole spectrum.

To provide for photometric measurements, a reflecting collimator with a slit was arranged so that the spectrum of the sun, suitably reduced in brilliance by platinised quartz screens, should be thrown on a falling photographic plate (from the same batch of plates as that used for the eclipse observations), whilst a graduated wedge was slowly

moved across the slit with its density gradient perpendicular to the slit. Provision was made for inserting the collimator when required between the siderostat and the grating.

Sunlight was to be thrown on the slit by an auxiliary plane mirror fed by a beam from the siderostat slightly deflected from the position in which it was used during the eclipse.

This whole equipment demanded much careful adjustment and it was successfully accomplished by Mr. Butler.

Interferometer Observations.—On the suggestion of Dr. Carroll, provision was made for photographing the corona through a Fabry and Perot *étalon*, in the hope that thereby the velocities in the line of sight of different parts of the corona might be deduced from measurements of the distortion of the fringes from perfectly circular form, and that possibly the width of the green coronal line might be found and hence an indication of the temperature of the coronal matter.

For this purpose a monochromatic image of the corona was to be obtained by means of a 4-inch plane grating, so oriented that the light of the green coronal line was reflected on to the interferometer system. The green line was chosen because it seemed to give a monochromatic image having the greatest contrast to the continuous background. Accordingly, interferometer plates (65 mm. in diameter) were mounted in a special holder with invar distance-rods to keep their faces 15 mm. apart, and the image of the corona was to be displaced to one side of the ring system, so that the arcs of the rings from about the 20th to the 40th might fall across it.

To secure a comparison system of rings, light from a mercury arc lamp was thrown on the system through a filter transmitting only the green line of mercury, the region of the plate which was to embrace the corona being masked off meanwhile.

As but little information was available to give a trustworthy guide to the exposure needed, it was planned to give two exposures, 2 seconds and 20 seconds, based on estimates made from results obtained in a study of the corona with an objective grating in 1901 by Professor Newall, who suggested that if the lateral displacement of the coronal image over the ring system was made in the position-angle of the axis of rotation of the sun, the relative displacement of the rings at the ends of the equatorial diameter might give direct indications of the rotation of the corona.

The plates of the *étalon* were silvered by cathode sputtering in the laboratory of the Solar Physics Observatory, and a density of 0·6 for the combined plates was chosen as the most suitable compromise between the desirability of narrow fringes and small loss of light.

Much help in the design of the system and in its preliminary adjustments was given by Professor Bryant, who also took charge of its erection and operation during the eclipse. To Professor Bryant the expedition owes much for the unstinted help which he rendered in many other ways.

The compiling of this report has served to recall the large amount of work expended both in the preparations in England and in the erection and adjustment of the instruments in Norway. If it also serves to recall the sense of extreme disappointment that the eclipse was not seen, it

brings back a vivid recollection of the sympathy received on all sides, especially from the Norwegians, in spite of a fairly widely prevalent idea that the unusually bad weather throughout June was to be ascribed to the coming eclipse.

The Total Solar Eclipse of 1927 *June* 29: *Report of the Cambridge Expedition to Colwyn Bay.*

1. *The Purpose of the Expedition.*—The purpose of the expedition was to obtain photographic records of the infra-red spectrum of the chromosphere and of the corona, if possible, by the use of Abney plates.

2. *Members of the Expedition.*—The expedition was organised by research students of Gonville and Caius College, Cambridge, acting under the direction of Lt.-Col. F. J. M. Stratton, M.A., and eventually comprised:

Assistant-Professor H. Dingle, Imperial College of Science and Technology; Dr. R. J. Clark, Caius College and University of Edinburgh; Dr. D. C. Rose, Caius College, Cambridge; Dr. W. A. Waters, Caius College, Cambridge; Dr. T. E. Allibone, Caius College, Cambridge; Mr. G. Owen, Caius College and University College, Bangor; Mr. I. C. Jones, Caius College and University College, Aberystwyth; Mr. R. O. Redman, St. John's College, Cambridge; Mr. R. W. Ditchburn, Trinity College, Cambridge; Mr. H. M. Cave, Trinity College, Cambridge; Mr. C. E. Wynn-Williams, Trinity College and University College, Bangor.

3. *Site Chosen for the Expedition.*—As it was desired to observe from a point on the coast of North Wales, the portion of that coast lying within the belt of totality was inspected by Mr. G. Owen and Mr. I. C. Jones, and finally the old telegraph station at Llysfaen, near Colwyn Bay, was chosen. This was on a hilltop at latitude 53° 16′·8 N., longitude 3° 39′·8 W., at about $\frac{3}{4}$ mile N.W. of the calculated central line of totality. For this point Mr. R. O. Redman calculated the times of second and third contacts as $5^h\ 23^m\ 31^s$ and $5^h\ 23^m\ 53^s$ G.M.T. respectively.

The selected site was shared with the expedition of the Royal Irish Academy for investigations of atmospheric electricity, acting under the direction of Professor J. J. Nolan.

4. *Apparatus.*—The instruments prepared for the eclipse were:

(1) A prism spectrograph of Littrow type.
(2) A paraboloidal objective-grating spectrograph.

Both instruments were prepared in Cambridge by members of the party, who wish to express their indebtedness for the loan of the following portions of the instruments:—

To Mr. Merfield of Melbourne for a paraboloidal reflection grating, specially designed for infra-red work; to Mr. A. F. Lindemann for a 12-inch parabolic mirror; to Dr. C. G. Siggs, Mr. M. H. Whitelegge,

and Captain M. A. Ainslie, for smaller mirrors; and to the Joint Permanent Eclipse Committee for a 16-inch cœlostat.

Both instruments were designed by Dr. Rose and Dr. Clark, and were first assembled in the Cavendish Laboratory.

(a) *The Prism Spectrograph.*—The prism for use in the spectrograph consisted of a piece of extra dense flint-glass, obtained from Messrs. Parsons, for which the transparency in the infra-red was specially tested in Cambridge. It was moulded, ground, and polished by Messrs. Adam Hilger Ltd., to the form of a 30° prism, the back surface being silvered. This half prism was used with a $6\frac{1}{2}$-inch paraboloid mirror of 146·4 cms. focal length to build a spectroscope similar to the Wadsworth * type, giving a dispersion of about 70 A. per mm. at λ8600 A.

Arrangements were made for a comparison spark spectrum of manganese to be put on each plate before or after the exposure on the eclipsed sun.

(b) *The Grating Spectrograph.*—Mr. Merfield's grating was mounted as an objective spectrograph for the infra-red portion of the spectrum, one of the first order diffracted images (dispersion about 20 A. per mm.) being used as it was of the greatest intensity. For eliminating lines of the superposed second order spectrum, a red dye was obtained from Liverpool University by Mr. R. W. Ditchburn. It had been tested for infra-red transparency and was to be used as a dilute aqueous solution placed in a plate-glass cell in front of the grating.

5. *Photographic Plates.*—Attempts were made in Edinburgh University by Dr. R. J. Clark to prepare infra-red sensitive plates as described by Abney and by Ritz, but no satisfactory plates were obtained previous to the date of the eclipse.

The projected programme was therefore altered so as to admit of the use of both neocyanine and kryptocyanine dyed plates obtained from Messrs. Kodak Ltd.

The neocyanine plates were supersensitised with ammonia before use.

6. *Preparations for the Spectrophotographic Observations.*—The cœlostat was prepared for use at the Royal Observatory, Greenwich. All other mirrors were resilvered at the Solar Physics Observatory, Cambridge, with the assistance of Dr. Carroll and Mr. Butler.

At Llysfaen brick pillars were erected for the instruments, for which moveable canvas shelters were constructed. During the three weeks preceding the eclipse much trouble was experienced from the prevailing high winds, which necessitated repeated strengthening of the shelters.

The erection of the framework of the instruments was completed a fortnight before the eclipse, but on account of the weather it was not possible to complete all the necessary adjustments until almost the last moment.

The prism spectrograph was mounted so that the light, reflected horizontally from the upper portion of the cœlostat, was reflected by the 12-inch paraboloid mirror to form an image on the slit which was so placed as to be tangential to the image of the sun at a point midway between the points of second and third contact.

* *Phil. Mag.*, **38**, 137 (1894).

The grating spectrograph was placed so as to receive horizontally the beam of light from the lower portion of the cœlostat after reflection from a plane mirror at an angle of 45°.

Two exposures were to be taken on the prism spectrograph, one on a neocyanine plate and the other on a kryptocyanine plate, each with its comparison spectrum. The first exposure was to begin at the moment when the cusp reached the point of contact of the sun's image and the slit, and to continue until mid-totality ; the second exposure was to last for the corresponding period after mid-totality. On account of the position chosen for the slit, exposures of over two minutes might have been secured on each plate for the upper chromosphere and corona.

With the objective-grating spectrograph two exposures (together including the whole period of totality) were to be made on one neocyanine plate, the position of which was to be shifted immediately after the first flash.

The following tasks were allotted to the observers :—

Professor Dingle was to give warning signals for the exposures on the prism spectrograph by observation of the image on the slit, while Dr. R. J. Clark and Dr. W. A. Waters were to carry out the exposures. For the grating spectrograph, Dr. D. C. Rose was to give the signals by watching the appearance of the bright line spectrum as seen through a Thorpe grating mounted on binoculars, while Mr. G. Owen and Mr. H. M. Cave were to carry out the exposures.

Time-counting during the necessary period of the eclipse was carried out by Mr. I. C. Jones ; Mr. R. O. Redman was allotted the final adjustment of the cœlostat ; Dr. T. E. Allibone the adjustment of the 12-inch mirror ; and Mr. R. W. Ditchburn the working of the comparison spark.

On the day of the eclipse no photographs could be taken as the sky was completely overcast and rain was falling. All the instruments, however, were uncovered in preparation, and seconds were counted during the time of totality.

From examination of the sky in the direction of the sun, it was estimated that the totality occurred about 2 seconds before the calculated time, though the edge of the shadow could not be seen distinctly.

7. *Experiments with Radio Telegraphy.*—In conjunction with this expedition, experiments on the strength of short wireless waves during the eclipse were carried out by Mr. C. E. Wynn-Williams, who was co-operating with the Radio Research Board.

A Reinartz 30-metre receiver, with a single low-frequency amplifying valve, was used to pick up the special transmission from the station PCJJ, Eindhoven (30·2 metres) between 3.30 and 7.30 a.m. (G.M.T.) on the mornings of June 28, 29, and 30. Measurements of the signal intensity were made by the shunted phone method.

When plotted the results showed an extremely well-defined fading-out of signals to at least one-tenth of their normal strength a few minutes before totality. From then until about 6.5 a.m. (G.M.T.) the signals were much too weak to be measured with accuracy, except at odd intervals. A very gradual increase in signal strength took place after 6.5 a.m. until the end of the observations.

The results on the day before and the day after the eclipse showed

an increase in signal strength between 3.30 and 7.30 a.m. with no such marked fading as was observed on the day of the eclipse.

8. *Conclusion.*—The members of the expedition wish to thank the Government Grant Committee of the Royal Society for a grant of £40, which has partly defrayed the cost of the flint-glass prism.

They also wish to express their thanks to Lt.-Col. F. J. M. Stratton, M.A., for his invaluable help and advice during all the preparatory work.

They desire to record the fact that invaluable assistance was given in Colwyn Bay by the members of the Colwyn Bay District Council, through whom free cartage for the instruments was obtained. In addition, they thank the Rev. A. J. Costain, M.A., for permission to use the dark-room at Rydal Mount School, Colwyn Bay, for most of their photographic work.

They are also deeply indebted to Mr. W. Greenfield of the Colwyn Bay Information Bureau for his numerous services during all stages of the work.

Total Solar Eclipse, 1927 *June* 29: *Report of the Observations made at Stonyhurst College Observatory.*

Owing to a small cloud covering the eclipsed sun during the time of totality, the photographic and main part of the observatory programme was unfortunately completely frustrated.

Stonyhurst was some 6 miles from the central line. According to Dr. Crommelin's calculations, totality was expected to last from $5^h\ 24^m\ 0^s$ to $5^h\ 24^m\ 22^s$ G.M.T.

Apparatus and Scheme of Work.

1. The 15-inch Perry Memorial equatorial. With this instrument, it was proposed to photograph the corona, employing a Wratten light filter No. 74ϵ. This filter transmits light of wave-length λ5100 to λ5700, with maximum intensity at λ5300. It was therefore hoped to get a picture of the corona in practically coronium light.

2. The Dallmeyer portrait camera, attached to the equatorial, was to be used to secure as much extension of the corona as possible, specially rapid, non-reversible, chromatic plates, prepared by Messrs. Ilford, being employed.

3. Through the kindness of the Royal Irish Academy, the Joint Permanent Eclipse Committee and the Astronomer Royal, the 4-inch, 19-foot focal length lens and tube used in the expedition to Sumatra in 1926 January was lent to Stonyhurst; and the 4-inch direct-vision prism used on the same occasion was also lent to us by Professor Sampson.

With these instruments it was intended to take first a direct photograph of the corona, and secondly, the flash at second contact.

4. The Hilger spectrograph was to be used on the cusps before and after totality, an erecting prism being used to place the cusps in position.

5. A Dallmeyer 6-inch telephoto system was lent to us by Mr. French of Manchester. This gave an image of the sun 32 mm. in diameter, and it was proposed with this to take a photograph of the corona.

Preparation.

1 and 2. The Perry Memorial equatorial, being a visual telescope, had never been used for direct photography, and a camera box had in consequence to be designed which could be fitted on at will. This was accomplished by Mr. Gibbs of Preston, who was most helpful in many other ways.

It was then discovered that there were three solid metal diaphragms in the lower half of the telescope tube, which cut down the field at the focal plane exposed to the full aperture of the object-glass to about 33 mm. As the image of the moon was 41 mm., it was essential, if the full benefit of the object-glass was to be utilised, that these diaphragms should be removed. This was accordingly done, and the tube adequately stiffened and thoroughly blackened inside. From visual observations, it was found that no deterioration in definition at any part of the field was introduced by the alterations. A sliding carrier in the camera box enabled the filter to be placed in a convenient position, and the best definition was determined by photographs on the moon. It was also found that better results were obtained with panchromatic rather than chromatic plates, and Messrs. Ilford accordingly supplied us with special rapid, backed panchromatic plates (8 in. × 6 in.).

The Dallmeyer 6-inch photographic camera was already in perfect adjustment. A yellow screen was fitted in front of the lens so as to cut out all blue and violet radiation from the early morning sky.

By a suitable rearrangement of the balancing weights, a very satisfactory drive by the clock was secured.

Father Swindells, S.J., assisted by Father Woodlock, S.J., of Liverpool, the Rev. H. Macklin, S.J., and two of the school students were responsible for operating the instruments. The plates were to be exposed one second after the word " Go " was given, and an exposure of 19 seconds was to be made.

3. The 4-inch, 19-foot focus coronograph was mounted equatorially on an iron mount firmly clamped on to a concrete pillar sunk about 3 feet into the ground and resting on solid clay. Three feet of the telescope tube projected beyond the declination axis fitting. At 12 feet from the same axis the telescope was firmly fixed to a stout wooden carriage by a suitably constructed steel arrangement designed by Father Rowland, an essential part of which was a hand-wheel running on an inch pitch screw for adjusting the telescope in declination. The carriage, mounted on three specially-constructed brass castors,

moved on a rigid slab of slate very firmly fixed in the meridian and parallel to the equatorial plane. A small clock-work motor was attached to the carriage, the wire round the drum being fixed to a winch on the southern edge of the slate slab.

A portion of the weight of the telescope was balanced by suitable weights, the remainder acting as drive for the clock. By winding or unwinding the winch, adjustments in right ascension could be effected.

A finder and screen were mounted on the telescope near the camera end, so that the crescent or eclipsed sun could be viewed while the plates were in position. The direct-vision prism was mounted on an L-shaped platform in front of the object-glass. The platform could be rotated into any required position, and the prism slipped in front of the object-glass or pushed aside with the greatest ease. The platform was adjusted in such a way that the arc at third contact would be normal to the direction of dispersion of the prism.

Finally, by resting two poles of unequal lengths on opposite sides of the tube, any vibrations set up by changing slides, etc. were quickly damped.

The whole arrangement worked very well, but it was felt that it entailed a very great deal of labour which hardly compensated, if at all, for any advantage over using a cœlostat and mounting the telescope horizontally. Further, there was this very great inconvenience, that the telescope could be pointed to the sun for only about one hour. The slate slab was so placed that the carriage on which the telescope rested was about the middle of the slab at the time of totality. This proved to be a very serious drawback indeed, as though the sun was visible up to about forty minutes before totality, it was then covered by a heavy bank of cloud, and only showed again seven minutes before second contact, when the final adjustments had to be made very rapidly.

The best focus was determined by a number of direct photographs of the sun on the few available occasions during the last three weeks before the eclipse, when the sun shone in the early morning.

Father O'Connor was in charge of this instrument; Mr. Haddock, one of the science masters at the college, was responsible for moving the prism into position, and three of the school students assisted in various ways.

The programme was to give 7 seconds exposure on the corona, and the last 6 seconds of totality on the flash at third contact, only allowing 8 seconds for the requisite changes. The prism is direct at $\lambda 3800$, and as it was hoped to secure a spectrogram as far into the red as a panchromatic plate would allow, it was necessary to alter the right ascension of the instrument immediately after the exposure on the corona. This was readily done by unwinding the winch $1\frac{3}{4}$ turns, a duty which devolved on one of the assisting students. The telescope was, moreover, so adjusted that the spectrum would lie somewhat diagonally across the plate (10 in. $\times$ 8 in.), and so allow for as great an extension as possible. It was realised that the red end would not be in good focus, but it was hoped that some useful information might be obtained even in this part of the spectrum.

A considerable amount of practice was required to enable us to

carry out this programme during the very limited time of totality, but the difficulties were all successfully surmounted.

4. The Hilger spectrograph is housed in the west wing of the meteorological building, with the result that it cannot be used before about 10 a.m. It was therefore decided temporarily to set it up in the small transit room adjoining the equatorial dome. Mr. Hindle of Haslingden made us an excellent 12-inch flat which was used as the rotating mirror of the cœlostat, the old 12-inch flat already in our possession being used as the stationary mirror.

The alteration entailed a considerable amount of structural work, which, however, was successfully carried out by the college carpenter and mason, the details and distribution of the various parts of the instrument in its old site being exactly reproduced in the new.

Father Rowland, assisted by the Rev. J. Lawrence, S.J., of Oxford, was in charge, and spectrograms in different parts of the spectrum as far into the red as panchromatic plates would allow were to be attempted.

Owing to the break of the weather in June there was not a single opportunity for testing the instrument in the early morning under more or less eclipse conditions, and on the morning itself it was quite evident that it would be useless to try to get anything; so that this part of the programme was definitely abandoned.

5. The Dallmeyer 6-inch telephoto arrangement was fixed on to the cross mounting. A wooden tube and camera box to carry full-sized plates was constructed, and a yellow screen was fitted between the lenses. The Rev. F. Plant, S.J., with the help of two students, operated the instrument.

Yet another large telephoto camera, giving an image of the sun 17 mm. in diameter, was lent to us by Mr. Vernon Price of Cobham, Surrey. This reached Stonyhurst only two days before the eclipse. It was mounted in the cricket fields 500 yards due south of the observatory. With this instrument it was proposed to take three snaps of the sun at intervals of five minutes, starting as soon as possible after first contact, the exposures being accurately timed with one of the observatory chronometers. Three similar exposures before fourth contact, one as near as possible to second contact, and another immediately after third contact, with all times accurately noted, was to complete the programme.

The Rev. J. O'Hea, S.J., was in charge, assisted by three of the students. The object in view was to secure data for the determination of the times of the four contacts.

The first four exposures were successfully made, the fourth just at second contact showing eight distinct Baily beads. The fifth exposure was spoilt owing to the camera moving, the last three were spoilt by clouds.

Finally, in accordance with the recommendations made by the sub-committee appointed by the Gassiot committee, arrangements were made for quick runs of four hours' duration on the magnetographs, from 4^h to 8^h G.M.T. on the 28th, 29th, and 30th —a special change-speed gear having been designed by Father Rowland.

The curves obtained are beautifully clear, and throughout the periods of the quick runs on all three days the magnetic conditions were exceptionally quiet, and so were well suited to bring out any deviations from the normal effect of solar radiation as affecting magnetic conditions. As the curves show that there was not the slightest variation at or near the time of the eclipse, it appears to be clearly established that the screening action of the moon is without magnetic effect under these conditions.

In addition to individual drills, general drills were carried out under eclipse conditions on the day preceding the eclipse. Father O'Leary, S.J., of Dublin, was responsible for giving the warning time-signals before the commencement of totality and for counting seconds during totality. Father Rowland, assisted by Rev. J. Lawrence at the Frodsham half-second chronometer, would give the signal "Go" by observing the "flash" through a transparent Thorpe replica grating fitted to the objective of a prismatic monocular magnifying 8 diameters.

The Morning of the Eclipse.

The morning was cloudy and misty, but there were clear patches of sky. At $4^h\ 15^m$ G.M.T. the sun was shining through the mist, but by $4^h\ 30^m$ a bank of cloud covered the upper portion of the sun, and first contact could not be observed. The sun, however, shortly afterwards emerged from the cloud only to be effectively screened a few minutes later by a heavy stratus cloud. A light breeze was blowing from the S. by W. and a break in the cloud was seen to be approaching the sun's position. At $5^h\ 17^m$ the now rapidly diminishing crescent again appeared, a small cloudlet approaching it from the south. At the signal "30 seconds more" the crescent was still visible, though becoming very faint owing to the approach of the cloudlet mentioned above. Father Rowland was compelled to turn the monocular *direct* on to the sun, and was able to see the crescent suddenly disappear when he gave the signal "Go." The time was $5^h\ 23^m\ 58^s{\cdot}9$., $1^s{\cdot}1$ earlier than that predicted by Dr. Crommelin. *Nothing* was now visible, but we nevertheless carried out our programme.

When the crescent disappeared at second contact there was absolutely nothing left to keep in the field of view, and Father Rowland's instrument actually drifted off from the assumed position of the sun. The first intimation of the end of totality was the appearance of the emerging crescent seen with the other eye, without instrumental aid, and immediately the signal "Stop" was given at $5^h\ 24^m\ 22^s{\cdot}4$.

Father O'Connor, who was intently watching for the appearance of the first Baily bead to close down his exposure for the flash, did so about 1·5 seconds before the signal "Stop" was given. Assuming that the signal was 1·5 seconds too late, this would give exactly 22 seconds for the duration of totality as predicted by Dr. Crommelin.

The other exposures had all been closed down at the signal "Twenty."

On developing the plates, the only one which showed any result, in addition to the four mentioned earlier, was that on the 6-inch Dallmeyer attached to the 15-inch equatorial. This camera was working

at F4. On the plate, the chromosphere from position-angle 180° to 270° is well marked with coronal matter showing faintly to about ¼ of a diameter from position-angle 210° to 250°. A faint trace of the rest of the chromosphere can also be seen. This shows that the eclipsed sun was emerging from the cloudlet some 4 seconds before the end of totality.

A striking confirmation of the time of second contact was obtained from that determined by the Rev. J. O'Hea, who had a good view of the corona, although only 500 yards away. On reducing his time to the observatory station, it worked out at $5^h\ 23^m\ 58^s{\cdot}8$.

It may be mentioned that the boys who were all in the cricket fields, some of them not more than 250 yards away from the observatory, were also fortunate enough to get a view during the time of totality.

In addition to the work carried out at the observatory, Professor F. M. da Costa Lobo, director of the observatory of the Coimbra University, with his assistant Mr. Madeira, erected two equatorially-mounted cinematographs for the purpose of taking films during the whole period of the eclipse. They were assisted by Captain L. Robertson, one of the members of the staff, and four of the students. Their programme was completely carried out, but any results they may have obtained are not yet to hand.

The instruments were mounted on the flat roof of the college, and thus a commanding view of the whole horizon from north through east to south was obtained.

The Total Solar Eclipse, 1927 *June* 29 : *Report of the National Physical Laboratory Expedition to Penhill.* By J. L. Haughton, D.Sc.

(*Communicated by the Secretaries.*)

Site.—The site chosen was on the southern slopes of Penhill Beacon, near Leyburn, Yorkshire. The position, as determined from the Ordnance Survey Map, was : Latitude 54° 16′·5 N., longitude 1° 54′·7 W., and was 1550 feet above sea-level, the hill rising to the N. and W. to a height of over 1800 feet. The apparatus was mounted in a gully running approximately N.E. and S.W., but closed on the S.W. end by a bank. This afforded considerable protection from the wind, while leaving a perfectly clear horizon from nearly N., through E., to about S.E. All the party camped in light-weight tents on the site.

Apparatus.—The apparatus consisted of a 4-inch equatorial telescope driven by a home-made clock, in which the control was regulated by a fan that opened out and increased the air resistance when the required speed was exceeded. The telescope carried a 4-inch diameter Dallmeyer camera of 33-inch focal length, with a 4-plate reversing back. This was kindly put at the disposal of the party by the Royal Observatory. A shutter was carried in front of the camera, and independently of the camera and telescope, so as to avoid vibration due to working the shutter.

A large prism, lent by Messrs. Hilger, was mounted in front of a portrait lens camera (the property of Dr. E. H. Rayner) in order to photograph the flash-spectrum, while a small direct-vision spectroscope, lent by Messrs. Browning, was intended for timing the second and third contacts by the appearance of the flash-spectrum.

A Ciné Kodak camera, having a lens working at F/3·5, was lent by Messrs. Kodak. In addition to these cameras we had a number of ordinary hand and stand cameras, and one with 3 lenses and plates for 3-colour photography of the corona. For this instrument Messrs. Dallmeyer lent us 3 identical lenses of 6-inch focal length working at F/3·5. Ilford tricolour filters and panchromatic plates were used.

The time-signals were received from Daventry by means of a portable wireless set, and a pendulum, beating seconds on an electric bell, was arranged so that it could be started by means of a switch at the moment that totality was observed with the 4-inch telescope, while seconds were to be counted backwards from 23 to 0, at the beats of the bell. A ship's chronometer was used for the actual timing, being checked by the Daventry time-signals at intervals before and after totality.

Temperatures were observed on a solar radiation thermometer and by means of a multiple thermo-couple working in conjunction with a thread recorder. The cold junction of the thermo-couple was in water in a buried thermos flask, the temperature of the water being measured by a carefully calibrated mercury thermometer. The couple was calibrated after the expedition returned.

Personnel and Work.

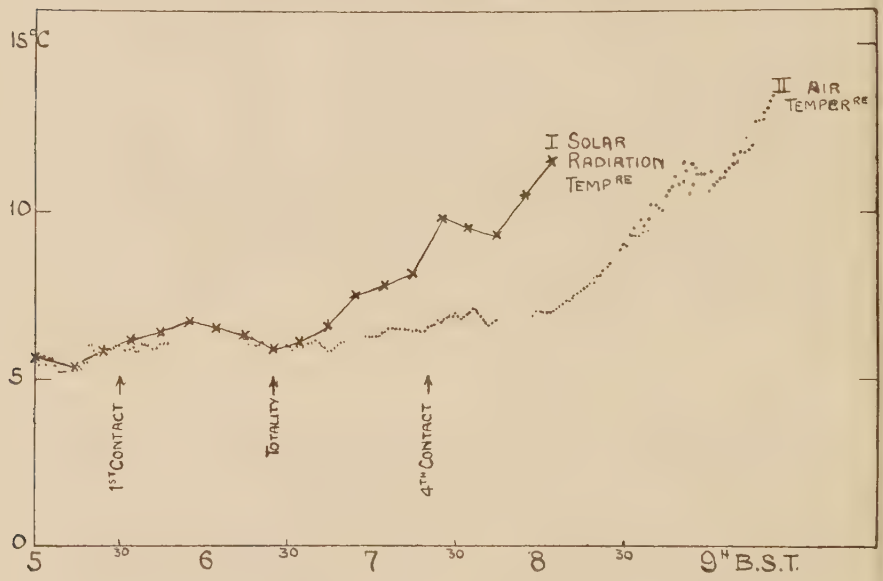
J. L. Haughton, D.Sc., F.Inst.P.	4-inch equatorial.
J. Cartland, M.Sc.	Time.
J. W. Jenkin, Ph.D., B.Sc.	4-inch Dallmeyer.
L. H. Tippett, M.Sc., A.R.C.S.	Spectroscopes.
Miss M. L. V. Gayler, D.Sc.	Temperatures.
Miss I. H. Hadfield, M.Sc.	Colour and photometric photographs.
L. M. Clark, B.A., Ph.D.	Ciné camera.
Mrs. W. Cartland.	Approaching shadow photographs.

Programme of Work Proposed.—It was proposed to take twelve photographs of the partial phase at specified times, five before and seven after totality; and during totality to take three photographs of 16^s, 2^s and $\frac{1}{4}^s$ duration; all with the 4-inch Dallmeyer. Two colour photographs of the corona were to be taken, one on an Agfa colour-plate and one with the tricolour camera. Both the exposures were to last throughout totality. Dr. Gayler was also to attempt to make a drawing of the corona. Photographs of the flash-spectrum were to be taken at the commencement and end of totality, and, in addition, photographs of white sheets were to be taken: (1) with the Ciné camera, in order to obtain motion pictures of the shadow bands, and (2) with an ordinary camera giving a 10-second exposure. This was to be used

for photometric purposes. An attempt was to be made to photograph the approaching and receding shadow with a reflex camera, and, finally, temperature readings were to be taken on the solar radiation thermometer at 10-minute intervals from $5^h\ 0^m$ (B.S.T.) to $8^h\ 0^m$, the thread recorder registering the air temperature at 1-minute intervals over the same period.

The results obtained with the Ciné camera suggest that, even had shadow bands been visible, there would not have been enough light to obtain photographs of them.

The apparatus was brought to Leyburn station on the morning of June 25 by an advance guard consisting of Dr. Jenkin and myself.



Here we were met by Mr. H. Brown, a farmer in the district, who conveyed the apparatus by horse and cart to the site. I should like to express my grateful thanks to this gentleman for the help he was to the party in many ways and my admiration of the way he and his horse succeeded in getting the apparatus up the trackless hillside without any damage being done. Tents were erected and apparatus was unpacked in a downpour of bitterly cold rain and a gale of wind, and little progress was possible. Other members of the party arrived that evening, and a cold, wet, and generally uncomfortable night was passed. The fly-sheet of the tent occupied by Dr. Jenkin and myself was torn to ribbons by the gale, but the tent held out, though it was necessary to go out and look after the pegs on more than one occasion. When morning came we found that the stores' tent had collapsed and some of the apparatus was lying in pools of water; however, no harm was done. Next day it rained most of the time and little more could be done than

making the tents more secure and erecting the remaining ones for the rest of the party, some of whom arrived on that day and the others on Monday.

Monday and Tuesday were spent in erecting apparatus, doing what checking and adjustment of the equatorial and clock drive was possible with an overcast sky, and in rehearsing; unfortunately very little of the latter was possible.

The next day (Wednesday) we were up by about 4 o'clock (B.S.T.), and carried out what Mr. Hinks has described as the "solemn farce" of going through the programme as though the sun was visible. We did catch one or two glimpses of the sun through clouds, but never for more than 2 or 3 seconds, and not at all during totality.

The times of commencement and end of totality as judged by the fall and rise of darkness were very marked and were estimated by Mr. Cartland to occur at $6^h\ 24^m\ 30^s$ and $6^h\ 24^m\ 53^s$. Both these times are 2 seconds earlier than the time calculated for Penhill. The calculations were made by measuring the distance from Richmond on the eclipse map issued by the Joint Permanent Eclipse Committee and then applying the correction given by the latest calculations published.

The temperature given by the solar radiation thermometer rose steadily till $5^h\ 55^m$ from 5°·4 C. to 6°·8 C., then fell to 5°·9 C., after which it rose steadily (Curve I). The fall at about $7^h\ 30^m$ was due to a slight shower of rain at about that time.

The air-temperature record is given in Curve II. Unfortunately the recorder ceased to mark twice during the eclipse, but the temperature appears to have remained steady within ± 0°·2 C. at 6° C. between $5^h\ 15^m$ and $6^h\ 50^m$, after which it rose fairly rapidly. The fall due to the shower at $7^h\ 30^m$ is also shown in this record. The irregularity at about $9^h\ 0^m$ is due to disturbances caused by taking down the tent near the apparatus.

In conclusion I would like to convey the cordial thanks of the party to all who assisted us by lending apparatus and by advice and encouragement, and my personal thanks to my colleagues, who gave up so much of their time and energy in a forlorn attempt to make a success of the expedition.

The Total Solar Eclipse of 1927 *June* 29: *Report of the Observations made at Criccieth.* By C. C. Roberts.

(*Communicated by the Secretaries.*)

A party of volunteers assembled at Criccieth under the organisation of Mr. Albert Taylor, who had previously observed eclipses in S.W. Africa and in Brazil.

The Town Council appointed a special committee who rendered every assistance in their power to make the observations successful. A large field, at the western end of the town, with an uninterrupted view of the part of the sky where the eclipse would take place, was lent by

the Lord Lieutenant of the County, and the police undertook to exclude the general public therefrom. Col. Drage, Commandant of the Criccieth Boy Scouts, placed their Drill Hall at Mr. Taylor's disposal. This, besides affording an excellent workshop and store-room, contained in addition a good-sized dark-room.

A 21-inch siderostat, the property of Sir Francis McClean, was sent by the Norman Lockyer Observatory at Sidmouth from Greenwich, where the mirror was resilvered. This was erected and suitably housed by Mr. Taylor with the assistance of local labour provided by the Eclipse Committee.

The next member of the party to arrive was Mr. C. C. Roberts, who brought with him a spectrograph camera, the property of Mr. Walter Scutt, H.M.I., of Acton, who, to his great disappointment, was unable to be present on account of professional duties; this instrument had two 60° prisms and a lens of 34-inch focal length. It was intended to give two exposures with infra-red plates 5 seconds after the commencement and 5 seconds before the conclusion of totality. A collimator of 20-inch focal length was attached for focussing, and being provided with a hinged shutter could be used to give the exposures after removing the slit and lens.

Mr. Roberts also brought with him a 6-inch Herschelian mirror* of 78-inch focal length, as a good wooden tube for it was available at Criccieth. Later there arrived in a friend's car Mr. G. A. S. Atkinson from Crewe with his concave Rowland grating suitably mounted for photographic work; he also brought a 6-inch reflecting telescope of 26-inch focal length, with which it was hoped to secure short-exposure photographs of the inner corona.

Mr. Dunn of the Electrical Department of the L.M.S. Railway Co., who was a member of the party, rendered most valuable assistance in the construction of shutters and dark slides to fit the telescopes and the grating spectroscope.

In the absence of sun, stars, gas, and electric light, the greatest difficulty was experienced in adjusting the focus of the different instruments and rating the driving-clock of the siderostat. Borax in a candle flame, and in a petrol lamp, had to suffice for illuminating collimator slits.

Professor J. H. Shaxby of Cardiff, and his colleague Dr. Deniol Williams of Aberystwyth University College, brought a special photometer, and this was the only instrument which was able to secure quantitative results.

The instruments were at length all carefully adjusted and dress rehearsals of the duties of the observers carried out, but all in vain. When the portable wireless set tuned-in to Daventry announced, "Stand by for 6.22," the whole party stepped out of the observation shed into the pouring rain to note just a blue-black colour of the clouds for 21 seconds, and totality was over.

The party unanimously wish to record their appreciation of the kind hospitality afforded to them by Mr. Riddeck and his family, whose house adjoins the field in which the instruments were set up.

* Lent by Mr. Martin of Greenwich Observatory.

Selective Radiation-Pressure and the Structure of a Stellar Atmosphere.
By E. A. Milne.

It is generally believed * that the reversing layer of a star is a region in which radiation-pressure becomes increasingly effective in supporting the atoms against gravity. The radiation-pressure in question is that arising from *selective* absorption—the line absorption visible in spectra. So far as the author is aware, it has not yet been shown why selective radiation-pressure should begin to play a conspicuous rôle only near the outside of a star. The present note shows in a simple way how the effect arises, and traces the continuous change from interior conditions to boundary conditions.

The radiation-pressure on an elementary layer of matter, or rather the force on it due to radiation-pressure, is proportional to the product of the net flux of radiation across the layer and the absorption coefficient. In the selective effect we have to consider the flux in radiation of frequency ν, say $\pi F_\nu \Delta\nu$, and the selective coefficient of absorption κ_ν. Now in the interior of a star, F_ν is itself inversely proportional to κ_ν, and the product $\kappa_\nu F_\nu \Delta\nu$ has the same value whatever be κ_ν. Thus the selective radiation-pressure is simply the normal contribution of an interval $\Delta\nu$ to the total radiation-pressure. But at the boundary of a star, in thermodynamic equilibrium, $\pi F_\nu \Delta\nu$ cannot fall below the black-body radiation for the surface temperature T_0, and here, accordingly, since κ_ν is large compared with the general coefficient of absorption κ, the product $\kappa_\nu F_\nu \Delta\nu$ may become comparable with, or even exceed, the general radiation-pressure proportional to κF.

Another way of stating the matter is as follows: Consider a point in the interior where the temperature is T. The outward flux of radiation past this point will approximately correspond to some higher temperature T_+; the inward flux to some lower temperature T_-. The more opaque the material, the nearer will T_+ be to T, and likewise T_- to T. The temperatures T_+ and T_- are functions of the frequency ν for the element of radiation considered, and the difference $T_+ - T_-$ is inversely proportional to κ_ν. But F_ν is proportional to $T_+ - T_-$. The bigger is κ_ν, the smaller is $T_+ - T_-$ and the smaller the net flux of ν-radiation. The two streams of radiation, outward and inward, become increasingly equal as κ_ν increases, and as far as their pressure is concerned they tend to neutralise one another. This effect is almost exactly compensated by the additional opacity of the atoms to ν-radiation, and we get the product $\kappa_\nu F_\nu$ independent of κ_ν. But at the boundary of the star the inward flux is non-existent and there is no neutralisation of the two streams. The atoms are exposed to the full brunt of the outward stream alone, and their

* See, *e.g.*, Russell and Stewart, *Astrophys. Journ.*, **59**, 208, 1924; Milne, *Proc. Phys. Soc. London*, **36**, 103, 1924, and *Proc. Manchester Lit. Phil. Soc.*, **71**, No. 1, 1926.

intense opacity to ν-radiation gives rise to a large selective radiation-pressure.

A more detailed mathematical treatment may be of some interest. We assume local thermodynamic equilibrium, *i.e.* we assume that at each point there is a definite value for T by whatever thermometric property of the *material* the temperature is judged. This is, of course, not true in the boundary layers of a star. It can be proved,* however, that the extent to which thermodynamic equilibrium holds locally depends simply on the density; the more the atoms are battered about by collisions, the more closely will the emission at any point be $\kappa_\nu B_\nu(T)\rho dx$ (where $B_\nu(T)$ is Planck's function), *i.e.* the more closely will it depend on the temperature judged by the relative numbers of atoms in different states and the less it will depend on the incident radiation. As we approach the interior of a star, local thermodynamic equilibrium sets in; as we approach the exterior, monochromatic radiative equilibrium (equilibrium in each separate frequency) sets in. The effect of selective radiation-pressure in the latter case is fully illustrated by the general theory of the chromosphere. Here we are first concerned to show that selective radiation-pressure rises into importance near the boundary even in the region in which local thermodynamic equilibrium holds.

It is sufficient to neglect curvature and consider material stratified in parallel planes. We take the case of a single absorption line.

Let B_ν denote Planck's function $(2h\nu^3/c^2)(e^{h\nu/kT}-1)^{-1}$. Let

$$B = \int B_\nu d\nu = \sigma T^4/\pi,$$

where σ is Stefan's constant. We define the optical thickness τ by

$$\tau = \int_0^x \kappa\rho dx \quad . \quad . \quad . \quad . \quad (1)$$

x being measured inwards from the boundary. As a function of τ we shall write $B_\nu = B_\nu(\tau)$. We also introduce the optical thickness τ_ν for ν-radiation, defined by

$$\tau_\nu = \int_0^x \kappa_\nu \rho dx \quad . \quad . \quad . \quad . \quad (2)$$

We can also regard B_ν as a function (in a given star) of τ_ν, and we shall then write $B_\nu = b_\nu(\tau_\nu)$. The temperature T at each point is known from investigations on integrated radiation. Thus if the net flux in integrated radiation is $\pi F = \sigma T_1^4$, then

$$T^4 = \tfrac{1}{2}T_1^4(1 + \tfrac{3}{2}\tau) \quad . \quad . \quad . \quad . \quad (3)$$

and

$$B = \tfrac{1}{2}F(1 + \tfrac{3}{2}\tau) \quad . \quad . \quad . \quad . \quad (3')$$

Let $I_\nu(\tau_\nu, \theta)$, $I'_\nu(\tau_\nu, \psi)$ be the outward and inward intensities in

* By a modification of Eddington's analysis in *The Internal Constitution of the Stars* (1926), p. 339.

ν-variation, in directions θ and ψ with the normal. The equations of transfer are

$$\cos\theta\frac{dI_\nu(\tau_\nu,\theta)}{d\tau_\nu} = I_\nu(\tau_\nu,\theta) - b_\nu(\tau_\nu) \quad . \quad . \quad . \quad (4)$$

$$\cos\psi\frac{dI'_\nu(\tau_\nu,\psi)}{d\tau_\nu} = -I'(\tau_\nu,\psi) + b_\nu(\tau_\nu) \quad . \quad . \quad (4')$$

The solutions of these equations are

$$I_\nu(\tau_\nu{}^0,\theta) = \int_{\tau_\nu{}^0}^{\infty} b_\nu(\tau_\nu)e^{-(\tau_\nu-\tau_\nu{}^0)\sec\theta}\sec\theta\,d\tau_\nu \quad . \quad . \quad (5)$$

$$I'_\nu(\tau_\nu{}^0,\psi) = \int_0^{\tau_\nu{}^0} b_\nu(\tau_\nu)e^{-(\tau_\nu{}^0-\tau_\nu)\sec\psi}\sec\psi\,d\tau_\nu \quad . \quad . \quad (6)$$

In (5) write $(\tau_\nu - \tau_\nu{}^0)\sec\theta = z$, in (6) write $(\tau_\nu{}^0 - \tau_\nu)\sec\psi = z$. Approximating by expanding the functions $b_\nu(\tau_\nu{}^0 + z\cos\theta)$, $b_\nu(\tau_\nu{}^0 - z\cos\psi)$ by Taylor's theorem to two terms, we find on dropping the index o,

$$I_\nu(\tau_\nu,\theta) = b_\nu(\tau_\nu) + \cos\theta\frac{db_\nu(\tau_\nu)}{d\tau_\nu} \quad . \quad . \quad . \quad (7)$$

$$I'_\nu(\tau_\nu,\psi) = b_\nu(\tau_\nu) - \cos\psi\frac{db_\nu(\tau_\nu)}{d\tau_\nu} - e^{-\tau_\nu\sec\psi}\left[b_\nu(\tau_\nu) - (\tau_\nu+\cos\psi)\frac{db_\nu(\tau_\nu)}{d\tau_\nu}\right] \quad . \quad (8)$$

The net flux of ν-radiation $\pi F_\nu\Delta\nu$ is given by

$$\pi F_\nu(\tau_\nu) = \int I_\nu(\tau,\theta)\cos\theta\,d\omega - \int I'(\tau,\psi)\cos\psi\,d\omega,$$

or, putting $\sec\psi = y$,

$$\pi F_\nu(\tau_\nu) = \frac{4\pi}{3}\frac{db_\nu(\tau_\nu)}{d\tau_\nu} + 2\pi\int_1^\infty\left[b_\nu(\tau_\nu) - \left(\tau_\nu+\frac{1}{y}\right)\frac{db_\nu(\tau_\nu)}{d\tau_\nu}\right]\frac{e^{-\tau_\nu y}dy}{y^3} \quad . \quad (9)$$

A sufficient approximation to the behaviour of the last integral is obtained by writing *

$$\pi F_\nu(\tau_\nu) = \frac{4\pi}{3}\frac{db_\nu(\tau_\nu)}{d\tau_\nu} + 2\pi\left[\tfrac{1}{2}b_\nu(\tau_\nu) - (\tfrac{1}{2}\tau_\nu+\tfrac{1}{3})\frac{db_\nu(\tau_\nu)}{d\tau_\nu}\right]e^{-\tau_\nu} \quad . \quad (10)$$

But

$$\frac{db_\nu(\tau_\nu)}{d\tau_\nu} = \frac{\kappa}{\kappa_\nu}\frac{dB_\nu(\tau)}{d\tau} \quad . \quad . \quad . \quad . \quad (11)$$

and so

$$\pi F_\nu(\tau_\nu) = \frac{4\pi}{3}\frac{\kappa}{\kappa_\nu}\frac{dB_\nu(\tau)}{d\tau}\left[1-\tfrac{1}{2}e^{-\tau_\nu}\right] + \pi\left[B_\nu(\tau) - \tau_\nu(\kappa/\kappa_\nu)\frac{dB_\nu(\tau)}{d\tau}\right]e^{-\tau_\nu} \quad . \quad (12)$$

The general coefficient of absorption κ is of the form † $\xi p/p'$, where ξ may be regarded as constant, p is the gas-pressure, and p' is the

* The second term in (10) actually falls off more rapidly than $e^{-\tau_\nu}$. This approximation, however, preserves a general inner consistency amongst our formulæ. Accurate formulæ could easily be used if necessary.

† *M.N.*, **85**, 768, 1925.

radiation-pressure $\frac{1}{3}aT^4$. Thus $\kappa \to 0$ as we approach the boundary of the star. On the other hand κ_ν, the selective coefficient, will remain approximately constant.* Thus we cannot assume κ_ν/κ = constant. Let us write, however,

$$\omega = \int_0^x \rho dx \quad . \quad . \quad . \quad . \quad (13)$$

Then

$$\tau_\nu(\kappa/\kappa_\nu) = \kappa\omega \quad . \quad . \quad . \quad . \quad (14)$$

Hence

$$\pi F_\nu(\tau) = \frac{4\pi}{3}\frac{\kappa}{\kappa_\nu}\frac{dB_\nu(\tau)}{d\tau}[1 - \tfrac{1}{2}e^{-\kappa_\nu\omega}] + \pi\left[B_\nu(\omega) - \omega\frac{dB_\nu(\omega)}{d\omega}\right]e^{-\kappa_\nu\omega} \quad (15)$$

where in the second term we have regarded B_ν as a function of ω.

As we penetrate deeper into the star, $e^{-\kappa_\nu\omega}$ tends rapidly to zero, owing to the high value of the selective absorption coefficient κ_ν. The second term in (15) then disappears and the first tends to

$$\frac{4\pi}{3}\frac{\kappa}{\kappa_\nu}\frac{dB_\nu(\tau)}{d\tau} = \frac{4\pi}{3}\frac{dB_\nu}{\kappa_\nu\rho dx} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

This is the well-known expression for the flux in the far interior. It gives rise to Rosseland's theorem † in the theory of the stellar absorption coefficient.

On the other hand, at the boundary ($\omega = 0$), πF_ν tends to

$$\pi B_\nu(0) \quad . \quad . \quad . \quad . \quad . \quad (17)$$

Even if the formula $\kappa = \xi p/p'$ is not accepted, so that $\kappa_0 \neq 0$, (17) is still very closely the limit of πF_ν at the boundary, since κ_0/κ_ν is in any case very small.

We now consider the force due to radiation-pressure, which on a layer ρdx is always

$$\frac{\pi F_\nu \Delta\nu \kappa_\nu \rho dx}{c}.$$

Inserting expression (15), we get

$$\rho dx\left[\frac{4\pi}{3c}\kappa\frac{dB_\nu(\tau)}{d\tau}\Delta\nu(1 - \tfrac{1}{2}e^{-\kappa_\nu\omega}) + \frac{\pi\kappa_\nu\Delta\nu}{c}\left(B_\nu(\omega) - \omega\frac{dB_\nu(\omega)}{d\omega}\right)e^{-\kappa_\nu\omega}\right] \quad (18)$$

In the far interior, this tends to

$$\frac{4\pi}{3c}dB_\nu\Delta\nu,$$

which is simply the contribution from the spectral interval $\Delta\nu$ to the

* Except, of course, for changes of ionisation, which are important. We are concerned here, however, to show that the phenomenon of predominant selective radiation-pressure near the outside of a star is independent of considerations of ionisation.

† *M.N.*, **84**, 525, 1924.

ordinary pressure of radiation. For integrating with respect to ν it gives

$$\frac{4\pi}{3c}dB = d(\tfrac{1}{3}aT^4)$$

since

$$B = (\sigma/\pi)T^4 \qquad \text{and} \qquad a = 4\sigma/c.$$

The general behaviour of the force due to radiation-pressure is, however, best seen by slightly re-arranging (18) and then integrating over the whole spectrum. We find

$$\rho dx\int_0^\infty \left[\frac{4\pi}{3c}\kappa\frac{dB_\nu(\tau)}{d\tau}(1-\tfrac{1}{2}e^{-\kappa_\nu\omega}) + \frac{\pi\kappa_\nu}{c}\left\{B_\nu(\omega) - \omega\frac{dB_\nu(\omega)}{d\omega}\right\}e^{-\kappa_\nu\omega}\right]d\nu$$
$$= \rho dx\left[\frac{4\pi}{3c}\kappa\frac{dB(\tau)}{d\tau} + \frac{\pi}{c}\int_0^\infty \kappa\left\{B_\nu(\omega) - \omega\frac{dB_\nu(\omega)}{d\omega} - \frac{2}{3}\frac{dB_\nu(\tau)}{d\tau}\right\}e^{-\kappa_\nu\omega}d\nu\right.$$
$$\left. + \frac{\pi}{c}\int_0^\infty (\kappa_\nu - \kappa)\left\{B_\nu(\omega) - \omega\frac{dB_\nu(\omega)}{d\omega}\right\}e^{-\kappa_\nu\omega}d\nu\right]. \qquad (19)$$

Since $B(\tau) = \frac{1}{2}F(1 + \frac{3}{2}\tau)$, the first term in this reduces to

$$\frac{\pi F\kappa\rho dx}{c} \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (20)$$

The second term may be shown to be always very small. For it tends rapidly to zero as ω increases. And for $\omega = 0$ its value is

$$\frac{\pi}{c}\kappa\left\{B(0) - \tfrac{2}{3}\left(\frac{dB(\tau)}{d\tau}\right)_{\tau=0}\right\},$$

which is zero by (3′). We accordingly neglect the second term in (19). The third term may also be simplified. We are only interested in its exact value for small values of ω, for which $B_\nu(\omega) - \omega dB_\nu(\omega)/d\omega$ is practically $B_\nu(0)$. This factor may be taken outside the sign of integration, since $\kappa_\nu - \kappa$ is zero except for a narrow region near the absorption line in question. It may therefore be written

$$\pi B_\nu(0)(\kappa_\nu - \kappa)e^{-\kappa_\nu\omega}\Delta\nu\rho dx/c,$$

where by κ_ν we now understand the mean value of the selective coefficient through the line; $(\kappa_\nu - \kappa)$ is of course the true selective absorption coefficient due to line absorption.

We have now for the force arising from radiation-pressure on the layer ρdx the expression

$$\frac{\rho dx}{c}[\pi F\kappa + \pi B_\nu(0)(\kappa_\nu - \kappa)\Delta\nu e^{-\kappa_\nu\omega}] \qquad . \qquad . \qquad (21)$$

This formula exhibits in a direct way the manner in which selective radiation-pressure rises into importance as the boundary of the star is approached. In the interior, even quite a short way in, the second term disappears. At the boundary the first term disappears if we take

$p = 0$ there and accept the theory giving $\kappa = \xi p/p'$; in any case the first term tends to a relatively small value at the boundary.

In my paper,* "Absorption Coefficients and the Pressure of Radiation in the Photospheric Layers of a Star," I have worked out the equilibrium of the photospheric layers, taking into account only the first term in (21). In that paper it was expressly stated that line absorption was ignored. We now see that that investigation holds at depths for which $e^{-\kappa_\nu \omega}$ is negligible compared with unity.

Mechanical Equilibrium.

We have tacitly supposed hitherto that there is zero radiation incident on the boundary. The "boundary" is, however, not the boundary of the star but the boundary of that portion of the star which is in local thermodynamic equilibrium. We must now take account of the back radiation from the portion of the star exterior to the region in local thermodynamic equilibrium.

Before we do this, some general remarks on the transition from local thermodynamic equilibrium to monochromatic radiative equilibrium may be inserted. It can be shown that under very general conditions, the true equation of transfer of ν-radiation is of the form †

$$\cos\theta \frac{dI_\nu(\tau_\nu, \theta)}{d\tau_\nu} = I_\nu(\tau_\nu, \theta) - \frac{\int I_\nu(\tau_\nu, \theta)\frac{d\omega}{\kappa\pi} + \eta B_\nu}{1+\eta} \quad . \quad (22)$$

where η is a parameter roughly independent of temperature, but proportional to the total density. It measures the extent to which collisions are effective in causing redistribution of energy amongst different frequencies, by encounters "of the second kind." As we penetrate the interior, η steadily increases, and (22) tends to the form (4), namely, the form for local thermodynamic equilibrium. As we approach the boundary, $\eta \to 0$, and (22) tends to the form

$$\cos\theta \frac{dI_\nu(\tau_\nu, \theta)}{d\tau_\nu} = I_\nu(\tau_\nu, \theta) - \int I_\nu(\tau_\nu, \theta)\frac{d\omega}{4\pi} \quad . \quad . \quad (23)$$

namely, the form for radiative equilibrium in ν-radiation.

An accurate theory of absorption lines would take account of this transition. The investigations of Schuster ‡ and Eddington § correspond in effect to taking a constant value of η. Eddington, in addition, assumes monochromatic radiative equilibrium in the ν-radiation just outside the absorption line, equivalent to adopting $\eta = 0$ here. This seems to me an error, as the conditions more nearly correspond to $\eta \to \infty$. Here we are going to attempt to take account of the transition by introducing a plane of discontinuity in η. We shall assume the

* *M.N.*, **85**, 768, 1925.

† In formulæ of this type, $d\omega$ denotes an element of solid angle. It must not be confused with the $d\omega$ ($=\rho dx$) of equation (13).

‡ *Astrophys. Journ.*, **21**, 1, 1905.

§ *Loc. cit.*

outer portions of the star divided into two regions, R_1 and R_2. In the upper, R_1, which corresponds to the chromosphere and upper reversing layer, we shall assume monochromatic radiative equilibrium, *i.e.* $\eta = 0$. In the lower, R_2, which corresponds to the lower reversing layer and photospheric layers,* we shall assume local thermodynamic equilibrium, *i.e.* $\eta \to \infty$.

Region R_1, being in monochromatic radiative equilibrium, is characterised by a constant net flux in ν-radiation, say $\pi F_\nu \Delta\nu$. Let $\pi G_\nu \Delta\nu$ be the back flux from R_1 to R_2. Then since $\pi B_\nu(0)\Delta\nu$ is the outward flux from R_2 at its boundary, we must have

$$F_\nu = B_\nu(0) - G_\nu \quad . \quad . \quad . \quad . \quad (24)$$

At depth † τ_ν in R_2, the back flux $\pi G_\nu \Delta\nu$ will be attenuated to $\pi G_\nu \Delta\nu e^{-\kappa_\nu \omega}$ to our order of approximation. Consequently, modifying (21), we find that the force arising from radiation-pressure on the element ρdx of R_2 is

$$\frac{\rho dx}{c}[\pi F\kappa + \pi(B_\nu(0) - G_\nu)(\kappa_\nu - \kappa)\Delta\nu e^{-\kappa_\nu \omega}] \quad . \quad . \quad (25)$$

The equation of mechanical equilibrium of R_2 is accordingly, using (24),

$$g = \frac{1}{\rho}\frac{dp}{dx} + \frac{\pi F\kappa}{c} + \frac{\pi F_\nu \Delta\nu(\kappa_\nu - \kappa)}{c} e^{-\kappa_\nu \omega} \quad . \quad . \quad (26)$$

In the chromospheric region R_1, κ the coefficient of general absorption is negligible. Taking account of the radiation-pressure arising from the constant net flux $\pi F_\nu \Delta\nu$, we find for the mechanical equilibrium of R_1

$$g = \frac{1}{\rho}\frac{dp}{dx} + \frac{\pi F_\nu \Delta\nu \kappa_\nu}{c} \quad . \quad . \quad . \quad (27)$$

It will be observed that (26) passes continuously into (27) at the plane of demarcation $\omega = 0$. Equations (26) and (27) exhibit the complete transition: photosphere—reversing layer—chromosphere. At any appreciable depth in R_2, $e^{-\kappa_\nu \omega}$ is negligible, and we get an equation where radiation-pressure arises solely from the constant net flux πF of integrated radiation. As ω decreases, the selective radiation-pressure due to ν-radiation grows in importance. The flux in ν-radiation, and with it the radiation-pressure, then become constant as we pass from R_2 conditions to R_1 conditions.

So far the analysis has been fairly general. In what follows we have in mind more particularly an atom such as ionised calcium, which can be considered to have only two stationary states. The analysis seems to me to be in effect more general than is implied by a restriction to atoms of the Ca^+ type, but I am not clear as to exactly how general it is. In an investigation of this kind it seems best to push ahead first and then afterwards see what restrictions are needed.

* Region R_2 is, of course, in radiative equilibrium as regards the integrated radiation.

† The zeros of x, of ω, of τ, and of τ_ν are in each case to be reckoned from the plane of demarcation R_1/R_2.

If a_ν is the atomic absorption coefficient, I have shown in papers on the chromosphere that

$$a_\nu \Delta\nu = \frac{h\nu B_{12}}{4\pi} = \frac{h\nu}{4\pi} \cdot \frac{c^2}{2h\nu^3} \cdot \frac{1}{\tau'} \cdot \frac{q_2}{q_1} = \frac{c^2}{8\pi\nu^2\tau'} \cdot \frac{q_2}{q_1} \quad . \quad (28)$$

where τ' is the mean life in the excited state, and q_2 and q_1 are the weights of the excited and normal states. This relation is perfectly general. If n_1 and n_2 are the numbers of atoms in the normal and excited states per cm^3, then a_ν is connected with the selective mass-absorption coefficient $\kappa_\nu - \kappa$ by the relation

$$(n_1 + n_2)m(\kappa_\nu - \kappa) = \left(n_1 - n_2\frac{q_1}{q_2}\right)a_\nu \quad . \quad . \quad (29)$$

where m is the mass of the atom.

Equations (26) and (27) now become

$$g = \frac{1}{\rho}\frac{dp}{dx} + \frac{\pi F\kappa}{c} + F_\nu \frac{c}{8\nu^2\tau' m}\frac{q_2}{q_1} \cdot \frac{n_1 - n_2(q_1/q_2)}{n_1 + n_2} e^{-\kappa_\nu \omega} \quad . \quad (26')$$

$$g = \frac{1}{\rho}\frac{dp}{dx} + F_\nu \frac{c}{8\nu^2\tau' m}\frac{q_2}{q_1}\frac{n_1 - n_2(q_1/q_2)}{n_1 + n_2} \quad . \quad . \quad . \quad (27')$$

In the region R_2, the ratio n_2/n_1 is given by

$$\frac{n_2}{n_1} = \frac{q_2}{q_1} e^{-h\nu/kT} \quad . \quad . \quad . \quad . \quad (30)$$

In the region R_1, it is shown in papers on the chromosphere that it is given by

$$\frac{n_2(q_1/q_2)}{n_1 - n_2(q_1/q_2)} = \tfrac{1}{2}F_\nu(1 + \tfrac{3}{2}t_\nu) \quad . \quad . \quad . \quad (30')$$

where t_ν is the optical thickness of R_1 measured from $x = -\infty$.

In each case the ratio n_2/n_1 is very small, and except for a "fully supported" chromosphere may be neglected.

Let μ be the coefficient of partial support of the high-level chromosphere. Then from (27')

$$F_\nu = \frac{8\nu^2\tau' mg}{c}\frac{q_1}{q_2}(1 - \mu) \quad . \quad . \quad . \quad (31)$$

approximately. Using this in (26') and (27'), we find approximately

$$g = \frac{1}{\rho}\frac{dp}{dx} + \frac{\pi F\kappa}{c} + g(1 - \mu)e^{-\kappa_\nu \omega} \quad . \quad . \quad (26'')$$

$$\mu g = \frac{1}{\rho}\frac{dp}{dx} \quad . \quad . \quad . \quad . \quad (27'')$$

as the equations of mechanical equilibrium of R_2 and R_1 respectively.

In these forms of the equations of equilibrium we have no specific reference to the properties of the Ca^+ atom, and it seems probable that

these equations hold generally for all atoms, p being understood as the partial pressure and ρ the partial density.*

A first integral of (26″) is readily obtained. If $p' = \frac{1}{3}aT^4$ is the radiation-pressure, we have

$$\frac{dp'}{dx} = \frac{\kappa\rho\pi F}{c} \quad . \quad . \quad . \quad . \quad (32)$$

Introducing into (26″), and integrating with respect to ω, we have

$$(p + p') - (p_0 + p'_0) = g\left[\omega - \frac{1-\mu}{\kappa_\nu}(1 - e^{-\kappa_\nu\omega})\right] \quad . \quad (33)$$

where p_0 and p'_0 are the pressure and (general) radiation-pressure at $\omega = 0$. Equations (32) and (33), combined with the physical formula for κ, $\kappa = \xi p/p'$, provide a pair of equations for the two unknowns p and p' as functions of ω. From p', T is then known as a function of ω, and thence, from p, ρ is known. So, from (32) x is known as a function of ω and the state of equilibrium in R_2 is completely known, apart from μ. I have not, however, succeeded in carrying out the necessary integration. The general effect of the exponential term in (26″) is to cause smaller pressure gradients in the uppermost layers, and hence reduced pressures in the reversing layer. This is seen from (33).

So far we have not determined μ, the coefficient of partial support. As far as we have gone, the star could build up regions R_1 and R_2, for a given line ν, with any value of μ. The only difference is that the bigger is μ, the greater is the pressure p_0 at the boundary of demarcation R_1/R_2. It appears to me that this apparent indeterminacy is a consequence of our arbitrary fixation of a definite plane of separation R_1/R_2. The physical difference between R_1 and R_2 arises essentially from the density or, what comes to the same thing, the pressure. If we take μ too large, the value of p_0 at R_1/R_2 will be too large for monochromatic equilibrium to be possible there. R_2 will then encroach on R_1, absorbing some of R_1's atoms until a new state of equilibrium is arrived at with a smaller μ. This is, of course, a mere speculation, to be rejected or confirmed later by consideration of the orders of magnitude involved. Such estimates are difficult to make, as they depend on a quantitative treatment of collisions of the second kind, and it has seemed better in this paper to dwell rather on the physical principles involved.

We may set about examining μ as follows. The outward intensity $I_\nu(t_\nu, \theta)$ at any point t_ν in R_1 is given by

$$I_\nu(t_\nu, \theta) = \tfrac{1}{2}F_\nu(1 + \tfrac{3}{2}t_\nu + \tfrac{3}{2}\cos\theta) \quad . \quad . \quad (34)$$

* But in $\kappa = \xi p/p'$, p is substantially the partial pressure of free electrons derived from all the atoms present. It may be remarked that there is an unsolved problem in connection with the equilibrium of a column of a mixture of atoms acted on by selective radiation-pressures. For an isothermal column under gravity only, Dalton's law (a theorem of pure thermodynamics) tells us that the atoms separate out according to their atomic weights as though each were present alone. It has not yet been ascertained theoretically whether a similar theorem holds when radiation-pressure acts in addition to a conservative field of force.

and hence the outward flux is

$$2\pi\int_0^{\frac{1}{2}\pi} I_\nu(t_\nu, \theta)\cos\theta\sin\theta d\theta = \pi F_\nu(1 + \tfrac{2}{3}t_\nu).$$

This must be continuous at $x = 0$ with the outward flux in ν-radiation from R_2, namely, $\pi B_\nu(0)$. Hence

$$F_\nu(1 + \tfrac{2}{3}t_\nu^0) = B_\nu(0) \quad . \quad . \quad . \quad (35)$$

or

$$(1 + \tfrac{2}{3}t_\nu^0)(1 - \mu) = \frac{cB_\nu(0)(q_2/q_1)}{8\nu^2\tau' mg} \quad . \quad . \quad (36)$$

if t_ν^0 is the optical thickness of R_1. Now by chromospheric theory, unless μ is nearly zero, the pressure at the base of R_1, p_0, is given by

$$p_0 = \frac{mg\mu t_\nu^0}{a_\nu} \quad . \quad . \quad . \quad . \quad (37)$$

Hence, eliminating t_ν^0,

$$\left(1 + \tfrac{3}{4}\frac{a_\nu p_0}{mg}\frac{1}{\mu}\right)(1 - \mu) = \frac{cB_\nu(0)(q_2/q_1)}{8\nu^2\tau' mg} \quad . \quad . \quad (38)$$

If p_0 is supposed known from pure physics, this is an equation for μ which has a single real positive root (<1), whatever the values of the constants involved. Here p_0 is the partial pressure of the atoms in question at the point at which the transition from local thermodynamic equilibrium to monochromatic radiative equilibrium occurs. The value of p_0 depends on the relative importance of radiative transitions and collision transitions, and involves the properties of all the other atoms present. A knowledge of the mass-absorption coefficient $\kappa_\nu = a_\nu/m$ is also required.

It must be confessed that the determination of μ is in an unsatisfactory state. Without it we are unable to find the emergent flux in the line, for F_ν involves the factor $1 - \mu$. We have seen that the region in local thermodynamic equilibrium produces an outward flux in the line of amount *

$$\pi\left[B_\nu(0) + \tfrac{2}{3}\frac{\kappa_0}{\kappa_\nu}\left(\frac{dB_\nu}{d\tau}\right)_0\right]\Delta\nu \quad . \quad . \quad . \quad (39)$$

The flux in the adjacent continuous spectrum is obtained by putting $\kappa_\nu = \kappa_0$ in this, giving

$$\pi\left[B_\nu(0) + \tfrac{2}{3}\left(\frac{dB_\nu}{d\tau}\right)_0\right]\Delta\nu \quad . \quad . \quad . \quad (40)$$

which, in virtue of the relation $T^4 = \frac{1}{2}T_1^4(1 + \frac{3}{2}\tau)$, can be shown to be approximately $\pi B_\nu(T_1)\Delta\nu$, the black-body emission in ν-radiation for the effective temperature of the star. These results for thermodynamic equilibrium are of course well known. They lead to the further well-known result that, however large κ_ν, the contrast due to thermodynamic equilibrium cannot be more marked than is given by the ratio $B_\nu(T_0)/B_\nu(T_1)$. Any further deepening of the line originates in the layers

* This follows from (15) on putting $\omega = 0$.

not in thermodynamic equilibrium. For atoms producing in effect a single line, such as Ca^+, the residual flux must further be reduced at least to $(8\nu^2\tau' mg/c)(q_1/q_2)$, but it may be still further reduced by the factor $(1-\mu)$. One deduction we can make from (38): if $B_\nu(o)<(8\nu^2\tau' mg/c)(q_1/q_2)$, μ must have a value of the same order as unity—it cannot be nearly o. A "fully-supported" R_1, *i.e.* a high-level chromosphere, is then impossible. This agrees with a deduction made in an earlier paper.

Given μ, (35) fixes t_ν^0, the optical thickness of R_1. In my first paper on the Ca^+ chromosphere, the outward flux in R_1 at the plane R_1/R_2 was made equal to $B_\nu(T_1)$, and we had a relation equivalent to

$$F_\nu(1+\tfrac{3}{4}t_\nu^0) = B_\nu(T_1) \quad . \quad . \quad . \quad (41)$$

Relation (35) seems preferable. It demands a smaller value of t_ν^0 than before, hence a slower outward rate of decrease of density for a fully supported chromosphere. Taylor's recent * estimate of μ from eclipse observations, which uses (41) in effect, would have to be slightly increased if (35) be adopted.

Mathematically the complete treatment of a stellar atmosphere promises to be a complicated problem. We have local thermodynamic equilibrium shading off into monochromatic radiative equilibrium; we have mechanical equilibrium under a pressure gradient and general radiation-pressure shading off into equilibrium under a small pressure gradient and selective radiation-pressure; and we have changes of ionisation from level to level causing changes in the selective absorption coefficients. In the present paper I have attempted to present equations exhibiting the second of these phenomena by ignoring the third and replacing the first by a discontinuity—a discontinuity, however, not of pressure or density but of kind of equilibrium.

Summary.

It is shown that the effect of radiation-pressure in an absorption line is of no importance in the interior of a star, or in the photospheric layers, but rises rapidly into predominance as the boundary is approached. Formulæ are obtained which exhibit the transition, and are applied to write down the equations of equilibrium of the outer parts of a star. For this purpose the outer layers are divided into two regions, a lower region R_2 in which local thermodynamic equilibrium holds, and an upper region R_1 in which there is an equilibrium of radiation in each separate frequency. In the former, R_2, which corresponds to the photosphere and lower reversing layer, absorption lines begin to be formed and selective radiation-pressure rises into importance. In the latter, R_1, which corresponds to the upper reversing layer and chromosphere, absorption lines are deepened and selective radiation-pressure balances a constant fraction of gravity. How much the lines are deepened, and what fraction of gravity is ultimately balanced, are problems demanding further knowledge of the physical properties of the atoms, namely, the pressure or density at which the transition from

* *M.N.*, **87**, 616, 1927.

local thermodynamic equilibrium to monochromatic radiative equilibrium takes place. The bigger is this pressure, the thicker is R_1, the more obstruction it offers to the flow of radiation and the blacker is the line.

The University, Manchester:
1927 *August.*

Note added 1927 *September* 10.—The analysis in the later part of the paper appears to be valid for any type of atom which is not undergoing *cyclical* transitions amongst a number of stationary states. Thus transitions of the type $s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow s_1$ are excluded.

Stellar Equilibrium and the Influence of the Distribution of Energy-production. By E. A. Milne.

1. *The Problem.*—Eddington's famous solution of the problem of stellar equilibrium involved in the first instance an approximation "$\kappa\eta$ = constant." Here κ denotes the coefficient of opacity at any point distant r from the centre, and η denotes the ratio of the average rate of production of energy per gram inside the sphere of radius r to the average rate of production of energy per gram for the whole star. He afterwards discussed the extent to which, for a star built on the model "$\kappa\eta$ = constant," the relation $\kappa\eta$ = constant is in fact satisfied. Later still he worked out in detail the solution for the extreme case of a star with a point-source of energy at its centre. A full account of these investigations is contained in Chap. VI. of his recent book, *The Internal Constitution of the Stars* (1926). The main result of the discussion is that the luminosity of the star falls off with increasing concentration of energy-production towards the centre, but not sufficiently to account for the existing discrepancy between the stellar value of the coefficient of opacity and that calculated theoretically from pure physics.

So far no general solution of the problem of stellar equilibrium has been given when $\kappa\eta$ is not constant.* Even in the particular case of a point-source, the solution given by Eddington applies only to a star of one particular mass. In the present paper it is shown how to obtain a fairly general class of solutions when $\kappa\eta$ varies from point to point in the star.

At first sight the simplest procedure would seem to be to make $\kappa\eta$ some function of the temperature (*e.g.* a power). The equations are, however, then intractable. An alternative procedure is to adopt some function of the temperature to represent $1-\beta$, the ratio of radiation pressure to total pressure. We can then deduce the law of variation of $\kappa\eta$ implied by this law of variation of $1-\beta$. It is shown in the following paragraphs that by choice of an appropriate class of functions to represent $1-\beta$, the equations reduce to Emden's differential equation, and so the solution is known. The star's equilibrium remains of the

* Solutions for stars of large mass and of small mass, respectively, leading to Emden's differential equation, have been given by Jeans, *M.N.* **85**, 204 (1925).

type known as polytropic. When $\kappa\eta$ = constant, Eddington's result is that the polytropic index is 3. For the class of solutions here investigated the polytropic index is $3 - s$, where s is an arbitrary parameter occurring in the law of dependence of $1 - \beta$ or $\kappa\eta$ on the temperature. By choice of s, varying degrees of concentration of energy-production towards the centre of the star can be represented.

2. *The Equations.*—Let P be the total pressure, T the temperature, μ the molecular weight, R the gas-constant, ρ the density. Then we have

$$(1 - \beta)\mathrm{P} = \tfrac{1}{3}a\mathrm{T}^4 \quad . \quad . \quad . \quad . \quad (1)$$

$$\beta\mathrm{P} = (\mathrm{R}/\mu)\rho\mathrm{T} \quad . \quad . \quad . \quad (2)$$

Raise the second equation to the power $4 - s$ and divide by the first. We find

$$\mathrm{P}^{3-s}\frac{\beta^{4-s}}{1-\beta} = \frac{(\mathrm{R}/\mu)^{4-s}}{\frac{1}{3}a}\rho^{4-s}\mathrm{T}^{-s} \quad . \quad . \quad . \quad (3)$$

Now adopt *as an empirical assumption concerning the variation of* β *through the star the law*

$$\frac{1-\beta}{\beta^{4-s}} = \frac{1-\beta_c}{\beta_c{}^{4-s}}\left(\frac{\mathrm{T}}{\mathrm{T}_c}\right)^s. \quad . \quad . \quad . \quad (4)$$

where the suffix c denotes values at the centre. Then (3) becomes

$$\mathrm{P} = \mathrm{C}\rho^{\frac{4-s}{3-s}} \quad . \quad . \quad . \quad . \quad (5)$$

where

$$\mathrm{C}^{3-s} = \frac{(\mathrm{R}/\mu)^{4-s}}{\frac{1}{3}a}\cdot\frac{1-\beta_c}{\beta_c{}^{4-s}}\cdot\frac{1}{\mathrm{T}_c{}^s} \quad . \quad . \quad . \quad (6)$$

The equation of equilibrium being

$$\frac{d\mathrm{P}}{dr} = -g\rho = -\frac{\mathrm{GM}(r)}{r^2}\rho \quad . \quad . \quad . \quad (7)$$

where $\mathrm{M}(r)$ is the mass within radius r and G is the constant of gravitation, equation (5) shows that the equilibrium is of the polytropic kind with the polytropic indices n and k of Emden given by

$$n = \frac{1}{k-1} = \frac{1}{(4-s)/(3-s) - 1} = 3 - s \, . \quad . \quad (8)$$

We can now follow Emden's procedure. We eliminate $\mathrm{M}(r)$ from (7) and the relation

$$\mathrm{M}(r) = \int_0^r \rho 4\pi r^2 dr \quad . \quad . \quad . \quad . \quad (9)$$

The introducing variables u, ξ defined by

$$\rho = \rho_c u^{3-s} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$ar = \xi \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where

$$a^2 = \frac{4\pi\mathrm{G}}{\mathrm{C}(4-s)}\rho_c{}^{1-\frac{1}{3-s}}. \quad . \quad . \quad . \quad (12)$$

we obtain Emden's equation

$$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{du}{d\xi}\right) + u^{3-s} = 0 \quad . \quad . \quad . \quad (13)$$

The solution required is that for which $u = 1$ and $du/d\xi = 0$ at $\xi = 0$. The boundary of the star occurs at $\xi = \xi_0$, where $u(\xi_0) = 0$. We shall use the suffix 0 to denote boundary values.

3. *Mass.*—Substituting for ρ and r in (9) and using the differential equation we find

$$M^2 = \frac{(4-s)^3C^3}{4\pi G^3}\rho_c^{\frac{s}{3-s}}\xi_0^4\left(\frac{du}{d\xi}\right)_0^2 \quad . \quad . \quad . \quad (14)$$

where M now denotes the whole mass of the star, namely $M(r_0)$. Substitute in this for C. We obtain an expression involving ρ_c/T_c^3. To obtain a formula for ρ_c/T_c^3 divide (1) by (2) and substitute central values. We find

$$\frac{\beta_c}{1-\beta_c} = \frac{R/\mu}{\frac{1}{3}a}\frac{\rho_c}{T_c^3} \quad . \quad . \quad . \quad . \quad (15)$$

Equation (14) then reduces to

$$M^2 = \frac{(4-s)^3}{4\pi G^3}\frac{(R/\mu)^4}{\frac{1}{3}a}\frac{1-\beta_c}{\beta_c^4}\xi_0^4\left(\frac{du}{d\xi}\right)_0^2 \quad . \quad . \quad (16)$$

We see that given the mass, β_c is the root of a quartic equation. Equation (16) reduces to Eddington's quartic equation on putting $s = 0$, but it must be remembered that when $s \neq 0$ the numerical coefficient is different, as ξ_0 and $(du/d\xi)_0$ refer to the polytrope of index $(3 - s)$. From the numerical values in row (42) below it can be seen that $1 - \beta_c > 1 - \bar{\beta}$, where $\bar{\beta}$ denotes the constant value of β for $s = 0$, for the same M and μ.

4. *Mean Density.*—The mean density $\bar{\rho}$ is given as usual by

$$\frac{\bar{\rho}}{\rho_c} = -\left(\frac{3}{\xi}\frac{du}{d\xi}\right)_0 \quad . \quad . \quad . \quad . \quad (17)$$

5. *Central Temperature.*—From (7) we have

$$\frac{GM(r)}{r} = -\frac{1}{\rho}r\frac{dP}{dr} = -\frac{1}{\rho_c u^{3-s}}\xi\frac{d}{d\xi}(P_c u^{4-s}) = -\frac{P_c}{\rho_c}(4-s)\xi\frac{du}{d\xi} \quad (18)$$

But $P_c/\rho_c = (R/\mu\beta_c)T_c$ from (2). Inserting boundary values (18) then becomes

$$T_c = -\frac{\mu\beta_c}{R}\frac{GM}{r_0}\Big/(4-s)\xi_0\left(\frac{du}{d\xi}\right)_0 . \quad . \quad . \quad (19)$$

We shall see later that for given M, r_0 and μ, ρ_c and T_c decrease with increasing s. We shall also see that increasing s corresponds to increasing degrees of concentration of energy-production towards the centre. Thus for increasing degrees of energy-production towards the centre the star becomes cooler and more nearly homogeneous.

6. *Connection of* β *and* T *with* u.—We have $\rho = \rho_c u^{3-s}$, $P = P_c u^{4-s}$. Hence from (2)

$$\frac{T}{T_c} = u\frac{\beta}{\beta_c} \quad . \quad . \quad . \quad . \quad (20)$$

When β is constant ($s = 0$) the temperature is proportional to Emden's variable u. Equation (20) is the required generalisation of this when β is variable, for the model in question.

Inserting (20) in (1) we find

$$\frac{1-\beta}{\beta^4} = \frac{1-\beta_c}{\beta_c{}^4}u^s \quad . \quad . \quad . \quad . \quad (20')$$

which connects β with u.

7. *The Luminosity Relation.*—It remains to connect β with the flux of energy at any point. If $L(r)$ is the net flux crossing the sphere of radius r, then by the equation of radiative equilibrium (Eddington)

$$\frac{d}{dr}[(1-\beta)P] = -\frac{\kappa\rho}{c}\frac{L(r)}{4\pi r^2} \quad . \quad . \quad . \quad (21)$$

Dividing this by the equation of mechanical equilibrium (7) we find

$$\frac{d}{dP}[(1-\beta)P] = \frac{\kappa}{4\pi cG}\frac{L(r)}{M(r)}$$

$$= \frac{\kappa\eta}{4\pi cG}\frac{L}{M} \quad . \quad . \quad . \quad (22)$$

where L is the luminosity of the star and η is a factor expressing the distribution of energy-production, defined by

$$\frac{L(r)}{M(r)} = \eta\frac{L}{M} \quad . \quad . \quad . \quad . \quad (23)$$

The factor η will approach unity as the boundary of the star is approached, and will steadily increase inwards if energy-production is concentrated towards the centre. Differentiating out we find

$$1-\beta-P\frac{d\beta}{dP} = \frac{\kappa\eta}{4\pi cG}\frac{L}{M} \quad . \quad . \quad . \quad (24)$$

But from (1) and (4)

$$P=\tfrac{1}{3}aT_c{}^4(1-\beta)^{-1}\left(\frac{1-\beta}{\beta^{4-s}}\right)^{\frac{4}{s}}\left(\frac{\beta_c{}^{4-s}}{1-\beta_c}\right)^{\frac{4}{s}}$$

whence differentiating logarithmically

$$\frac{1}{P}\frac{dP}{d\beta} = -\frac{4-s}{s}\frac{4-3\beta}{\beta(1-\beta)} \quad . \quad . \quad . \quad (25)$$

Substituting (25) in (24) we find

$$L = \frac{4\pi cGM(1-\beta)}{\kappa\eta}\phi(\beta) \quad . \quad . \quad . \quad (26)$$

where

$$\phi(\beta) = 1 + \frac{s}{4-s}\frac{\beta}{4-3\beta} \quad . \quad . \quad . \quad (27)$$

Formula (26) is the generalisation of Eddington's famous luminosity formula for the model under discussion. Since L and M are constants, we have

$$\frac{\kappa\eta}{\kappa_c\eta_c} = \frac{(1-\beta)\phi(\beta)}{(1-\beta_c)\phi(\beta_c)} \quad . \quad . \quad . \quad (28)$$

which gives the variation of $\kappa\eta$ through the star as a function of β, and so from (4) or (20′) as a function of T or of the tabulated variable u.

If $s>0$, we see from (4) or (20′) that $1-\beta$ steadily decreases from the centre to the boundary. It is easily verified that $(1-\beta)\phi(\beta)$ also steadily decreases from the centre to the boundary, so that $\kappa\eta$ steadily decreases from the centre to the centre to the boundary.

If $\kappa \propto \rho T^{-(3+\nu)}$, then it is readily found that

$$\frac{1}{\kappa}\frac{d\kappa}{du} = -\frac{1}{u}\left[\nu + s\frac{(1-\nu)+\nu\beta}{4-3\beta}\right] \quad . \quad . \quad (29)$$

and so for $\nu = 0$ or $\nu = \frac{1}{2}$, κ steadily increases from the centre to the boundary if $s>0$. It follows that for our model, for $s>0$, η steadily decreases from the centre to the boundary. Thus for $s>0$, our assumption (4) implies concentration of energy-production towards the centre, and so is in this respect physically satisfactory.

8. *Behaviour of the Model in the Outer Layers.*—If we substitute for η from (23) in (26) we get

$$L(r) = \frac{4\pi cGM(r)}{\kappa}(1-\beta)\phi(\beta) \quad . \quad . \quad . \quad (30)$$

Now on our assumption (4), $1-\beta$ vanishes at the boundary. Hence according to (30) $L(r)$ vanishes at the boundary. We appear to have constructed a star of zero luminosity!

But it must be noted that even if we take $s = 0$, $1-\beta =$ constant, as in Eddington's investigations, the same difficulty arises when κ is supposed to vary as $\rho/T^{7/2}$. For when $s = 0$, ρ/T^3 is constant, κ is proportional to $T^{-\frac{1}{2}}$ and tends to infinity at the boundary, with the consequence from (30) that $L(r)$ vanishes at the boundary.

Eddington has shown, however, that we can validly apply formulæ of the type (30) at all points in the interior not too close to the boundary. For $s = 0, n = 3$, for instance, Emden's tables show that $1{\cdot}974/2{\cdot}015 = 0{\cdot}98$ of the mass is contained within $4{\cdot}50/6{\cdot}9011 = 0{\cdot}65$ of the radius. Practically all the energy radiated will be produced within this inner sphere. Hence at a point 0·65 of the radius out from the centre, we may take $L(r) = L$, $M(r) = M$, *i.e.* $\eta = 1$. Outside $0{\cdot}65r_0$, the polytropic model fails to represent the facts, but this does not much matter. The radius of the star will differ, it is true, from that calculated for the polytropic model, but we have dealt accurately with 0·98 of the mass, and so our calculations of luminosity and radiation pressure for the interior should hold good.

This is the argument as usually presented. The one doubtful point

is, does the polytropic model for the "core" give the right density and right temperature at $0{\cdot}65r_0$, in the example just cited? In the denominator of (30) κ occurs, and to apply (30) we have to know ρ and T at the boundary of the "core" in order to evaluate κ there.

The discussion of this point requires rather more delicate consideration.* It is well known that the structure of a star only becomes definite when the behaviour of $4\pi\epsilon$, the rate of liberation of energy per unit mass, and κ, the coefficient of absorption, are known. Actually when ϵ is known, η is known, and as Eddington has shown the structure of the star depends only on the product $\kappa\eta$. It is perhaps less commonly realised that when the structure of the star is known and the behaviour of κ (as a function of ρ, T, etc.) is known, then the behaviour of ϵ becomes definite. For $\kappa\eta$ is then known as a function of position, hence η is known, hence ϵ is known.

Accordingly the polytropic models discussed in this paper imply a definite law of variation of ϵ from place to place in the star. But we have seen that $L(r)$ approaches zero as the boundary is approached. Consequently if we adhere rigorously to the polytropic model, energy must be *disappearing* in the outer layers of the star. At a certain distance out from the centre ϵ must pass through a zero and change sign. In the central regions ϵ is positive and energy is liberated at each point; in the peripheral regions ϵ is negative and energy disappears at each point. In the central regions we have a distribution of *sources* of energy; in the peripheral regions we have a distribution of *sinks*.

Now we cannot suppose sinks to occur in an actual star. We must, therefore, replace the region of sinks by a model of some other structure. Calculation of density and temperature in the region of sinks are likely to be far out; for the presence of sinks will obviously cause the calculated temperature to be too low. We must, therefore, be careful only to apply formulæ of the type (30) in the region in which ϵ is positive. At the same time we want to apply it as far out as possible, so as to include as much as possible of the mass. It seems a reasonable assumption to suppose formula (30) valid up to the point where ϵ becomes zero. We then suppose $L(r)$ at this point to be equal to the observed luminosity L of the star;† $M(r)$, κ, and β remain to be calculated.

It may be repeated that procedure of this kind is not necessitated simply on account of our introduction of a variable β; it is also required even when β = constant if κ is supposed to vary according to the proportionality $\kappa \propto \rho/T^{3+\nu}$, where $\nu > 0$.

9. *Determination of the Zero of* ϵ.—We have from (21)

$$L(r) = -\frac{c}{\kappa\rho}4\pi r^2\frac{d}{dr}(\tfrac{1}{3}aT^4) \quad . \quad . \quad . \quad (31)$$

Now

$$L(r) = \int_0^r 4\pi\epsilon\rho \,.\, 4\pi r^2 dr \quad . \quad . \quad . \quad (32)$$

* The succeeding sections of the paper were written after a discussion with Professor Eddington, to whom I am much indebted.

† $L(r)$, which is zero at $r = 0$ and at $r = r_0$, has a maximum at the zero of ε. Thus we equate to L the maximum value of $L(r)$.

Differentiating to eliminate L(r) we have

$$\frac{4\pi\epsilon\rho}{c} = -\frac{1}{r^2}\frac{d}{dr}\left[\frac{r^2}{\kappa\rho}\frac{d(\frac{1}{3}aT^4)}{dr}\right] \quad . \quad . \quad . \quad (33)$$

This is a general relation in the theory of radiative equilibrium which has been given before by many writers.

Suppose now that

$$\kappa \propto \rho T^{-(3+\nu)} \quad . \quad . \quad . \quad . \quad (34)$$

For the models under discussion we have also

$$\rho \propto u^{3-s}$$
$$r \propto \xi$$
$$T \propto u\beta.$$

Hence (33) becomes

$$\epsilon u^{3-s} \propto -\frac{1}{\xi^2}\frac{d}{d\xi}\left[\xi^2\beta^{7+\nu}u^{\nu+2s}\frac{du}{d\xi}\left(1+\frac{u}{\beta}\frac{d\beta}{du}\right)\right] \quad . \quad . \quad (35)$$

Now from (20′) we find

$$\frac{u}{\beta}\frac{d\beta}{du} = -\frac{s(1-\beta)}{4-3\beta} \quad . \quad . \quad . \quad . \quad (36)$$

The factor

$$1 - \frac{s(1-\beta)}{4-3\beta}$$

changes comparatively slowly between the centre and the boundary. It is quite easy to take it into account, but it will simplify our formulæ and subsequent calculations if we treat it as a constant in differentiating out (35), and replace it by unity.

We then find from (35), on using Emden's equation (13), after a little reduction

$$\epsilon \propto u^{\nu+2s}\beta^{7+\nu}\left[1 - \frac{1}{u^{4-s}}\left(\frac{du}{d\xi}\right)^2\left\{\nu + s\frac{(1-\nu)+\beta(1+\nu)}{4-3\beta}\right\}\right] \quad (37)$$

It simplifies this a little if we use the proportionalities $(1-\beta) \propto \beta^4 u^s$, $T \propto u\beta$. We have finally

$$\epsilon \propto T^{\nu}\frac{(1-\beta)^2}{\beta}\left[1 - \frac{1}{u^{4-s}}\left(\frac{du}{d\xi}\right)^2\left\{\nu + s\frac{(1-\nu)+\beta(1+\nu)}{4-3\beta}\right\}\right] \quad (38)$$

In this $(1-\beta)^2/\beta$ is a function of T given in theory by (4).

Near the centre of the star, $(du/d\xi)$ is small, and we have approximately

$$\epsilon \propto T^{\nu}\frac{(1-\beta)^2}{\beta} \quad . \quad . \quad . \quad . \quad (39)$$

It is of interest to express this roughly as a power of T. If $y = (1-\beta)^2/\beta$ were an actual power of T, say $\propto T^{\lambda}$, we should have

$$\frac{1}{y}\frac{dy}{dT} = \frac{\lambda}{T}.$$

Actually
$$\frac{1}{y}\frac{dy}{d\mathrm{T}} = \frac{1}{\mathrm{T}}\frac{s(1+\beta)}{(4-s)-(3-s)\beta}$$
as is found by using (4). Consequently near the centre, ϵ varies roughly as T raised to the (variable) exponent
$$\nu + \frac{s(1+\beta)}{(4-s)-(3-s)\beta}.$$
Thus for $s = 0$, we have $\epsilon \propto \mathrm{T}^{\nu}$. Taking $1-\beta = 0{\cdot}3$, we have for $s = \frac{1}{2}$, $\epsilon \propto \mathrm{T}^{\nu+0{\cdot}2}$; for $s = 1$, $\epsilon \propto \mathrm{T}^{\nu+0{\cdot}44}$. These give some idea of the variation of energy-production near the centre.

Further out, however, ϵ changes in general much more rapidly, by (38). Only when both $\nu = 0$ and $s = 0$ is ϵ constant. For all other polytropes, ϵ has a zero where
$$u^{4-s} = \left(\frac{du}{d\xi}\right)^2\left[\nu + s\frac{(1-\nu)+\beta(1+\nu)}{4-3\beta}\right] \quad . \quad . \quad (40)$$
It ultimately becomes negatively infinite at the boundary unless $\nu + 3s \geqslant 4$, by (37).

10. *Numerical Calculation of the Zero of* ϵ. —As a preliminary to the calculation of luminosities, it is necessary to compute the zero of ϵ in each individual case. The calculations have been undertaken for Capella (brighter component).

All we need to know of the actual data for Capella is that for this star Eddington has found the value $1-\bar{\beta} = 0{\cdot}283$ for the polytrope $s = 0$, $n = 3$. We use the symbol $\bar{\beta}$ to denote the constant value of β for this polytrope.

The procedure is as follows. From (16) we have
$$\frac{1-\bar{\beta}}{\bar{\beta}^4}4^3\left[\xi_0{}^4\left(\frac{du}{d\xi}\right)_0^2\right]_{n=3} = \frac{1-\beta_c}{\beta_c{}^4}(4-s)^3\left[\xi_0{}^4\left(\frac{du}{d\xi}\right)_0^2\right]_{n=3-s} . \quad (41)$$

From Emden's tables, the values of
$$(4-s)^3\left[\xi_0{}^4\left(\frac{du}{d\xi}\right)_0^2\right]_{n=3-s}$$
are found to be

$s = 0$	$s = \frac{1}{2}$	$s = 1$		
260	207	157	.	. (42)

For $1-\bar{\beta} = 0{\cdot}283$, the values of $(1-\beta_c)$ are found to be by solution of (41),

$s = \frac{1}{2}$	$s = 1$			
0·308	0·338	.	.	. (43)

From these, from equation (20′), we can determine $1-\beta$ for any value of u.

Equation (40) has now to be solved by trial interpolations amongst Emden's tabulated values, using in each case the properly calculated value of β. The results for four different cases are shown in the last

four lines of Table I. The first line gives the boundary values for the case $\nu = 0, s = 0$ (ϵ = constant) and is put in for completeness. The prime ($'$) denotes values of the variables at the zero of ϵ.

TABLE I.

Case.	ν.	s.	ξ'.	ξ_0.	ξ'/ξ_0.	u'.	$1-\beta'$.	$1-\beta_c$.	$M(r')/M$.	T'/T_c.
1	0	0	6·901	6·901	1·000	0	·283	·283	1·000	0
2	0	½	2·892	5·417	·533	·3348	·248	·308	·820	·364
3	½	0	2·994	6·901	·433	·3579	·283	·283	·820	·358
4	½	½	2·423	5·417	·447	·4454	·263	·308	·682	·474
5	½	1	2·007	4·352	·461	·5276	·2675*	·338	·544	·583

11. *Transformations of the Luminosity Relation.*—For actual determinations of luminosity and coefficient of opacity, (30) requires a little transformation. Two forms are convenient, according as we wish to determine the luminosity in terms of the constant in the formula for the coefficient of absorption, or as we wish to determine the coefficient of absorption at the centre. Put

$$\kappa = \kappa_1 \frac{\rho}{\mu T^{3+\nu}} \quad . \quad . \quad . \quad . \quad (44)$$

From (1) and (2)

$$\frac{\rho}{T^3} = \frac{\frac{1}{3}a}{R/\mu} \frac{\beta}{1-\beta} \quad . \quad . \quad . \quad . \quad (45)$$

Then (30) becomes

$$L(r) = \frac{4\pi cG}{\kappa_1} \frac{R}{\frac{1}{3}a} M(r) T^\nu \frac{(1-\beta)^2}{\beta} \phi(\beta) \quad . \quad . \quad (46)$$

Inserting the values at the zero of ϵ, and taking $L(r') = L$, (46) becomes

$$L = \frac{4\pi cGM}{\kappa_1} \frac{R}{\frac{1}{3}a} \frac{M(r')}{M} \left(\frac{T'}{T_c}\right)^\nu \frac{(1-\beta')^2}{\beta'} \phi(\beta') T_c^\nu \quad . \quad (47)$$

This may be compared with the formula adopted by Eddington (*loc. cit.*, p. 134, equation (98·3)),

$$L = \frac{4\pi cGM}{\kappa_1} \frac{R}{\frac{1}{3}a} \cdot \frac{1}{2{\cdot}5} \cdot \frac{(1-\bar{\beta})^2}{\bar{\beta}} T_c^\nu \quad . \quad . \quad (48)$$

The values of the coefficient

$$\frac{M(r')}{M} \left(\frac{T'}{T_c}\right)^\nu \frac{(1-\beta')^2}{\beta'} \phi(\beta') \quad . \quad . \quad . \quad (49)$$

for Capella are tabulated in column 1 of Table II. below. The value of

$$\frac{(1-\bar{\beta})^2}{2{\cdot}5\bar{\beta}} \quad . \quad . \quad . \quad . \quad . \quad (50)$$

required by Eddington's formula is given in the last row of the table.

* This value looks erroneous, but I have been unable to detect any mistake in my arithmetic.

Formula (48) only becomes definite when T_c is known. By formula (19), the value of T_c for given mass and radius, is proportional to

$$\beta_c/(4-s)\xi_0 \left|\frac{du}{d\xi}\right|_0 .$$

For three different values of s, the values of $1/(4-s)\xi_0 \,|\, du/d\xi \,|_0$ are:

$s = 0$	$s = \frac{1}{2}$	$s = 1$	
0·856	0·703	0·601 .	. (51)

These numbers, multiplied by β_c, are given in column 2 of Table II., and their νth power in column 3. Column 4 gives the product of columns 1 and 3. The numbers in this column (4) are proportional to the luminosity of the star for given κ_1, or to κ_1 for given L.

TABLE II.

Case.	ν.	s.	(1).	(2) (T_c).	(3) (T_c^{ν}).	(4) (L).	(5) (κ_c).	η_c.
1	0	0	·1116	·614	1·000	·1116	·283	1·00
2	0	$\frac{1}{2}$	·0712	·487	1·000	·0712	·160	2·02
3	$\frac{1}{2}$	0	·0547	·614	·783	·0429	·139	2·03
4	$\frac{1}{2}$	$\frac{1}{2}$	·0464	·487	·697	·0324	·105	3·09
5	$\frac{1}{2}$	1	·0460	·398	·630	·0290	·090	4·17
(Eddington)			·0446	·614	·783	·0350	·113	(3·9)

Again, we can substitute for κ_1 in terms of κ_c by using the relation

$$\kappa_c = \frac{\kappa_1}{\mu}\frac{\rho_c}{T_c^{3+\nu}} \quad . \quad . \quad . \quad . \quad (52)$$

This gives

$$\kappa_c = \kappa_1 \frac{\frac{1}{3}a}{R}\frac{\beta_c}{1-\beta_c}\frac{1}{T_c^{\nu}},$$

and formula (47) becomes

$$L = \frac{4\pi cGM}{\kappa_c}\frac{M(r')}{M}\left(\frac{T'}{T_c}\right)^{\nu}\frac{(1-\beta')^2}{\beta'}\frac{\beta_c}{1-\beta_c}\phi(\beta') \quad . \quad (53)$$

The corresponding formula adopted by Eddington (*loc. cit.*, p. 124, equation (90·1)) is

$$L = \frac{4\pi cGM}{\kappa_c}\frac{1-\bar{\beta}}{2{\cdot}5} \quad . \quad . \quad . \quad . \quad (54)$$

The values of the coefficient

$$\frac{M(r')}{M}\left(\frac{T'}{T_c}\right)^{\nu}\frac{(1-\beta')^2}{\beta'}\frac{\beta_c}{1-\beta_c}\phi(\beta') \quad . \quad . \quad . \quad (55)$$

for Capella are tabulated in Table II., column 5. The entries are proportional to the value of the absorption coefficient at the centre. The last entry in column 5 is Eddington's coefficient $(1-\bar{\beta})/2{\cdot}5$.

It may be noticed that the entries in column 5 for cases 3, 4, 5 are closely proportional to the corresponding entries in column 4, *i.e.* $\kappa_c \propto L$ in these models. This implies that $\rho_c/T_c^{7/2}$ must be very closely the same for the three different polytropes concerned, for given mass and radius. This is easily checked directly. By (17) the values of ρ_c are proportional to $\frac{1}{3}\xi |d\xi/du|_0$, *i.e.* from Emden's tables to

$s = 0$	$s = \frac{1}{2}$	$s = 1$	
54·36	24·076	11·396	(56)

Numbers proportional to T_c have already been given in column 2 of Table II. Hence we find that $\rho_c/T_c^{7/2}$ is proportional to the numbers

$s = 0$	$s = \frac{1}{2}$	$s = 1$	
298	299	286	(57)

The constancy of $\rho_c/T_c^{7/2}$ for differing concentrations of energy-production only holds for the mass of Capella, as far as this calculation goes, but presumably the variation would not be large for any star of not widely differing mass. For a star of given mass, for varying s, we have $\rho_c \propto f_1(s)$, $T_c \propto \beta_c f_2(s)$, $1 - \beta_c \propto \beta_c^4 f_3(s)$, whence $\rho_c/T_c^{7/2} \propto F(s)\beta_c^{\frac{1}{2}}/(1-\beta_c)^2$. Consequently for any other mass, the numbers in (57) require changing in the ratio $\beta_c^{\frac{1}{2}}/(1-\beta_c)^2$.

Lastly, it is convenient to have before us the ratio η_c, given by

$$\lim_{r\to 0} \frac{L(r)}{M(r)} = \eta_c \frac{L}{M} \quad . \quad . \quad . \quad . \quad (58)$$

which affords a useful measure of the degree of concentration of energy-production towards the centre of the core. From (28) we have

$$\frac{\kappa'\eta'}{\kappa_c\eta_c} = \frac{1-\beta'}{1-\beta_c}\frac{\phi(\beta')}{\phi(\beta_c)} \quad . \quad . \quad . \quad . \quad (59)$$

Now at the zero of ϵ, we have $L(r') = L$, so that

$$\eta' = \frac{L(r')}{M(r')}\Big/\frac{L}{M} = \frac{M}{M(r')} \quad . \quad . \quad . \quad (60)$$

whilst

$$\frac{\kappa'}{\kappa_c} = \frac{\rho'}{T'^{\nu+3}}\frac{T_c^{\nu+3}}{\rho_c} = \frac{\beta'}{1-\beta'}\frac{1-\beta_c}{\beta_c}\left(\frac{T_c}{T'}\right)^{\nu} \quad . \quad . \quad (61)$$

Hence from (59)

$$\eta_c = \frac{M}{M(r')}\left(\frac{T_c}{T'}\right)^{\nu}\frac{\beta'}{(1-\beta')^2}\frac{(1-\beta_c)^2}{\beta_c}\frac{\phi(\beta_c)}{\phi(\beta')} \quad . \quad . \quad (62)$$

The values of η_c from (62) are tabulated in the last column of Table II. The last entry (in brackets) represents roughly the value of η_c adopted by Eddington; the factor 2·5 in the denominator of his luminosity formula was chosen to correspond to this value of η_c.

12. *Discussion of Results.*—The important results are column 4 of Table II. and the last column, η_c. As predicted by Eddington, increasing concentration of energy-production towards the centre (increasing s)

causes decreasing luminosity. In comparing Eddington's numerical value for the luminosity with the other entries in column 4, it should be remembered that he took his " core " as enclosing a mass $M(r')/M = 0{\cdot}9$, whilst in cases 4 and 5 our cores include masses $M(r')/M = 0{\cdot}68$ and $M(r')/M = 0{\cdot}54$. Thus, as compared with Eddington's, our cases correspond to more strongly concentrated energy-production than is suggested by the values of η_c, for the energy comes entirely from the core.

Thus case 5 represents considerably more concentrated energy-production than that adopted by Eddington. Yet the only effect is to reduce the luminosity in the ratio $29/35 = 0{\cdot}83$, or $0{\cdot}2$ magnitude. Conversely, for given luminosity, the value of κ_1, the constant in the formula for the absorption coefficient, as deduced from the observed mass and luminosity of Capella, is reduced in the same ratio, $29/35$, or say $6/7$. This is quite insufficient to account for the ten-fold discrepancy between the theoretical and " observed " values of the stellar absorption coefficient.

Broadly speaking, our calculations confirm Eddington's choice of a factor $2{\cdot}5$ to represent concentration of energy-production. This is the principal result of the paper. Eddington's factor was based on average calculated from the polytrope $n = 3$ as a first approximation. In our work we have used the proper polytrope corresponding to each degree of concentration, with the proper values of the temperature and density at each point, and any value which this paper possesses lies in this, that the more elaborate calculations lead to no appreciable alteration in Eddington's adopted luminosity formula.

One further point may be mentioned in connection with Eddington's choice of the constant $2{\cdot}5$. Calling this constant α, as he does, we find from comparison of (47) and (48) that the two will agree if

$$\frac{1}{\alpha} = \frac{M(r')}{M}\left(\frac{T'}{T_c}\right)^{\nu}\frac{(1-\beta')^2}{\beta'}\,\frac{\overline{\beta}}{(1-\overline{\beta})^2}\phi(\beta') \quad . \quad . \quad (63)$$

Thus $2{\cdot}5/\alpha$ is equal to the ratio of any entry in column 1, Table II., to the last entry. We see that for $\nu = \frac{1}{2}$, for $s = \frac{1}{2}$, and $s = 1$ the values of $2{\cdot}5/\alpha$ are $1{\cdot}04$ and $1{\cdot}03$. Thus our cases $s = \frac{1}{2}$ and $s = 1$ correspond very closely to Eddington's choice $\alpha = 2{\cdot}5$. The slight reduction in luminosity which we have found is not due to any change in α; it arises partly from the use of β' instead of $\overline{\beta}$, partly from the lowered value of the central temperature which occurs as a factor T_c^{ν} in both (47) and (48).

13. *Summary.*—(1) It is shown that the variation of Eddington's expression " $\kappa\eta$ " through a star may be allowed for by an appropriate choice of functional dependence on the temperature in such a way that the star remains polytropic. The polytropic index is $3 - s$, where s is an exponent occurring in the function already mentioned; s is equal to zero where $\kappa\eta$ is constant. Increasing values of s correspond to increasing degrees of energy-production to the centre. The density ρ varies less rapidly than T^{3-s} through the star.

(2) The ratio of radiation pressure to total pressure decreases from the centre of the star to the boundary when $s>0$. Its value at the centre is connected with the mass by a quartic equation of the same type as

Eddington's, with numerical coefficient appropriate to the polytrope $n = 3 - s$.

(3) With increasing s, the central density and central temperature decrease, for given mass and radius, the star becoming more nearly of uniform density. For $s = 0, \frac{1}{2}, 1$, the central densities are in the ratio 54 : 24 : 11, and for Capella the central temperatures are in the ratio 6 : 5 : 4. (See column 2, Table II.)

(4) If the absorption coefficient κ obeys a law $\kappa \propto \rho/T^{3+\nu}$, polytropic models always correspond to sinks of energy in the outer layers unless both $\nu = 0$ and $s = 0$. To determine the luminosity in terms of the mass and absorption coefficient, we must therefore confine attention to the inner core in which $4\pi\epsilon$, the rate of liberation of energy per unit mass, is positive. The luminosity formula must be applied at the place in the star where ϵ passes through a zero.

(5) The zero of ϵ and the resulting luminosities, are calculated for Capella (brighter component) for a variety of values of ν and s. For $\nu = \frac{1}{2}$ and $s = 1$, the resulting luminosity is only 0·2 magnitude less than that given by the formula adopted by Eddington. In the model $\nu = \frac{1}{2}$, $s = 1$, the average rate of evolution of energy per unit mass rises from the boundary to the centre in the ratio 1 : 4·2, but the actual liberation of energy is confined within the innermost 0·54 of the whole mass of the star. Eddington's adopted formula was based on the model $\nu = \frac{1}{2}$, $s = 0$ as a first approximation. The present paper shows that little alteration in his formula is required when we use the temperatures accurately appropriate to the degree of energy-concentration under consideration.

(6) The small reduction of luminosity found in this paper is insufficient to account for the known discrepancy between the astronomical and theoretical values of the stellar absorption coefficient. This is in accordance with Eddington's special investigation of the hypothetical star with a point-source of energy at its centre.

The University, Manchester:
1927 *September.*

On Liquid Stars:—Configurations of Stability, Long-period Variables, and Stellar Evolution. By J. H. Jeans.

1. In a previous paper * I investigated the stability of stellar structures, and found that no possible mode of generation of stellar energy could impart stability to a purely gaseous star. Whatever the means by which stellar energy is generated, the conditions for dynamical stability demand substantial departures from the laws obeyed by a perfect gas, and these must be so extensive that the condition of the star's interior is better described as liquid than as gaseous, although, of course, the outer layers must be always gaseous. The present paper contains a further study of the equilibrium and evolution of these liquid stars.

2. The main difficulty of the present investigation lies in the fact that the ordinary gas-laws are no longer obeyed in actual stars, and we

* *M.N.*, **87**, 400 (1927).

do not know what law connects pressure and density. In the previous paper I had assumed the fictitious law $p \propto \rho^{1+s}T$. While this cannot claim to represent the facts of nature, it served two useful purposes. In the first place on putting $s = 0$ it reduced to the ordinary gas-laws, and so enabled us to see that a star in which the gas-laws were exactly obeyed ($s = 0$) could not be stable. In the second place, I had shown in a still earlier paper * that stability or instability depended on the sign of $\delta(E - G)$, where E is the rate of emission and G the rate of generation of energy, and the special case of a model based on this fictitious law made it possible to determine which sign corresponded to stability and which to instability.

3. By an oversight I left the criterion of stability in a form which was not entirely freed from all relation to the law $p \propto \rho^{1+s}T$. The criterion for stability was found to be

$$\frac{d}{dT}(E - G) < 0 \quad . \quad . \quad . \quad . \quad (1)$$

with a further condition to ensure that the mode of generation of energy should not be explosive, but it was pointed out that this was only valid if $\lambda + 4 - 3s\lambda$ was positive. If s, which measured the deviation from the gas-laws, was so great as to make $\lambda + 4 - 3s\lambda$ negative, the stability criterion was reversed, and the condition for stability became

$$\frac{d}{dT}(E - G) > 0 \quad . \quad . \quad . \quad . \quad (2)$$

In discussing the special model in which $p \propto \rho^{1+s}T$, we had found series of homologous configurations, along each of which

$$r^{1-3s\lambda/(\lambda+4)}T = \text{const.},$$

where r is the distance of a characteristic element from the centre of the star, and so is proportional to R, the radius of the star. By logarithmic differentiation of this equation

$$(\lambda + 4 - 3s\lambda)\frac{dR}{R} + (\lambda + 4)\frac{dT}{T} = 0 \quad . \quad . \quad (3)$$

This shows that as $\lambda + 4 - 3s\lambda$ changes sign, dT/dR also changes sign; values of s which make $\lambda + 4 - 3s\lambda$ positive represent deviations from the gas-laws which are so great that heating is accompanied by expansion and cooling by contraction, as in a solid or a liquid. Using relation (3) we see that the two separate stability conditions (1) and (2) can be combined in the single condition that the star is stable if

$$\frac{dT}{dR}\frac{d}{dT}(E - G) > 0,$$

or, again, if

$$\frac{d}{dR}(E - G) > 0 \quad . \quad . \quad . \quad . \quad (4)$$

* *M.N.*, **85**, 916 (1925).

it still being supposed that the mode of generation of energy is non-explosive.

This expresses the quite general condition (for all values of s) that our special model shall be stable. The argument of the earlier paper already quoted * shows that in a star of any structure whatever, stability depends on the sign of $\frac{d}{dR}(E - G)$. Thus it follows that inequality (4) expresses the general condition for stability for any star, this being coupled with the condition that the mode of generation of energy shall not make the star explosively unstable.

4. In the former paper the condition that the star shall not be explosively unstable was obtained in the form †

$$\beta + 3\alpha - n < q \quad . \quad . \quad . \quad . \quad (5)$$

Here the rate of generation of energy per unit mass in the star is supposed proportional to $\rho^{\alpha}T^{\beta}$, the coefficient of opacity is supposed proportional to $\rho T^{-(3+n)}$, reducing to Kramers' law when $n = \frac{1}{2}$, and q is a small quantity. This condition rules out large positive values of α and β.

The normal process of generation of energy in a star certainly requires the annihilation of electrons ; there must, for instance, be many fewer electrons in the sun than in Plaskett's star (of mass 75 ⊙ +) or V Puppis (of mass 19 ⊙). These stars are destined in time to become similar to the sun, and by the time they are similar, most of the electrons they now contain will have been annihilated in the process of transforming matter into radiation.

The only way in which an electron can be annihilated is by coalescing with a nuclear proton, but the electron may be either bound or free when the coalescence takes place. If energy were generated by the coalescence of free electrons and nuclei, the frequency of coalescence would almost certainly be proportional to the number of collisions or encounters per unit time between free electrons and nuclei. This would give $\alpha = 1$, $\beta = \frac{1}{2}$, and a value of $3\alpha + \beta$, 3·5, which is too large for condition (5) to be satisfied. The possibility of energy being generated by free electrons coalescing with nuclei is accordingly ruled out. Thus the main part at least of stellar radiation must be generated by the annihilation of bound electrons. As a corollary, atoms which are stripped bare of electrons down to their nuclei must be immune from annihilation, so that a star in which most of the atoms are ionised down to their nuclei can only radiate very little energy.

I was originally led to this result as a hypothesis which was found necessary to explain observed facts, but it appears that it may now take rank as a proved fact, being a necessary deduction from the observed non-explosiveness of the stars. Observational confirmation is provided by the feeble emission of radiation by the white dwarfs and small stars, whether white or not, of very high density. Their observed densities show that they must consist, in the main, of atoms stripped bare to their nuclei, and their generation of energy per unit

* *M.N.*, **85**, 916 (1925).
† *M.N.*, **87**, 406 (1927), equation (15).

mass is almost of a different order of magnitude from that of normal stars of equal mass. In ergs per gramme per second, the sun's generation of energy is 1·90, that of Sirius B is 0·007, that of Procyon B at most about 0·005, while that of Wolf 359 (assuming its mass to be not less than $\frac{1}{4}\odot$) is less than 0·002.

5. The flux of radiation H at a distance r from the centre of a star is given by

$$H = -\frac{C\mu T^{6\cdot5}}{(N^2/A)\rho^2}\frac{dT}{dr}. \quad . \quad . \quad . \quad . \quad (6)$$

in which C is a constant, N and A are the atomic number and atomic weight of the stellar atoms, and the opacity coefficient k is supposed given by Kramers' law, $k \propto \rho/\mu T^{3\cdot5}(N^2/A)$. Under stellar conditions μ is very nearly equal to A/N and only varies slightly from star to star. Treating μ as a constant, equation (6) can be put in the alternative form

$$H = -\frac{C'}{N\rho^2}\frac{d}{dr}(T^{7\cdot5}). \quad . \quad . \quad . \quad . \quad (7)$$

where C′ is a new constant.

For a given star in the sky the value of H near the surface, the mean density $\bar{\rho}$ and the radius R are matters of observation. Keeping H, $\bar{\rho}$, and R fixed, we can obtain an infinite series of possible internal configurations for the star by keeping the density ρ unchanged at every point, and so keeping every element of the star in its original location, but varying T and N in such a way that $T^{7\cdot5}/N$ retains a constant value at each point. If this value is chosen to be equal to the value in one standard configuration in which the star is in radiative equilibrium, then each new configuration also will be in radiative equilibrium.

The configuration will be in dynamical equilibrium also if the dynamical equation

$$\frac{dp}{dr} = -g\rho \quad . \quad . \quad . \quad . \quad . \quad (8)$$

is satisfied at every point. Let us suppose that this was satisfied in the standard configuration of equilibrium from which we started. Since ρ has remained unchanged, the whole gravitational field has remained unchanged, and so also has g, the gravitational force. Thus we see that the configurations will be in dynamical equilibrium if the pressure p remains always equal to its value in the standard configuration from which we started.

6. Let us suppose this standard configuration to be one in which the star is in the gaseous state throughout, the gas-laws being everywhere obeyed. When this supposition is made, equations (7) and (8) enable us to calculate $T^{7\cdot5}/N$, and the further equation given by the gas-laws enables us to calculate T and N separately. I have calculated the following values of N^2/A for actual stars on the supposition that their substance obeys the gas-laws throughout :— *

V Puppis 195, Sirius 178, Sun 186, α Centauri B 148, Capella A 129.

* *M.N.*, **86**, 570 (1926).

These values were calculated for an assumed effective molecular weight μ equal to 2·2. This value for μ is certainly too small. In the previous paper we very roughly estimated N, the atomic number of actual stellar atoms to be about 68,* but in the present paper we shall find that N = 95 is a better value, so that stellar atoms are probably at least as complex and massive as uranium. Now for uranium completely broken up into nuclei and electrons, $\mu = 2{\cdot}56$. If we had taken $\mu = 2{\cdot}56$ in place of $\mu = 2{\cdot}2$, the calculated values of N^2/A would have been (approximately) †

V Puppis 720, Sirius 650, Sun 680, α Centauri B 540, Capella A 470.

For atomic numbers in the neighbourhood of 95, the value of N^2/A is about 37. Thus the foregoing numbers are, on the average, about 18 times too large.

7. Imagine that we leave the standard gaseous configuration for which the above values are calculated, and pass along the series of configurations discussed in § 5 until we come to a configuration for which N^2/A, and so also N, is reduced to one-eighteenth of its value in the gaseous configuration. To reduce N to one-eighteenth we must reduce $T^{7{\cdot}5}$ to one-eighteenth of its value in the gaseous configuration. Taking the 7·5th root of $\frac{1}{18}$, we find that we must reduce T throughout the star to 68 per cent. of its value in the gaseous configuration. For the star to be in dynamical equilibrium, the pressure at each point must be precisely equal to the pressure at that point in the gaseous configuration. The deficiency of pressure which is produced by lowering the temperature must be made good by the excess pressure resulting from the deviations from the gas-laws. We can hardly expect the deviations from the gas-laws to be so obliging as to provide exactly the required excess of pressure at each point and no more, so that the model we now have under consideration cannot give a perfect picture of an actual star, but it will serve for a preliminary discussion in which we are only trying to get a general idea of the state of things inside a liquid star.

When the temperature is reduced to 68 per cent. of its original value, the pressure of radiation, $\frac{1}{3}aT^4$, is reduced to 21 per cent. of its value in the gaseous state. As the total pressure is the same in the liquid as in the gaseous star (namely, the pressure necessary to support the superposed layers against gravitation), material pressure is somewhat increased, being equal to the material pressure in the gaseous star plus 79 per cent. of the pressure of radiation in the gaseous star. The effect of all this is that radiation pressure becomes quite small relative to material pressure even in the most massive stars, and becomes entirely insignificant in stars of moderate mass. In the sun, for instance, radiation pressure is only of the order of 1 per cent. of material pressure.

The relation between the luminosity, mass, and temperature of a star has been discussed by Eddington and myself on the supposition that the stars are perfectly gaseous structures, and the pressure of radiation has played a fundamental part in these discussions. It now appears that the values assigned to the pressure of radiation have been

* *M.N.*, **87**, 411 (1927). † *M.N.*, **86**, 572, equation (98).

in error by a quantity of the order of four times its true value. This invalidates the whole of the discussions, and any apparent success they may have achieved must have been purely fortuitous. In liquid stars radiation pressure may in general be disregarded and the luminosity mass-temperature relation must be examined *de novo.*

In place of the now vanished pressure of radiation, a new pressure becomes important, which may be described as the liquid pressure of the atoms. The free electrons are so small that they will always exert pressure in accordance with Boyle's law, so that in the liquid star, in which the temperature is reduced to 68 per cent. of its former value, the electrons exert only 68 per cent. of their former pressure. The total pressure being the same as before, this leaves 32 per cent. of the original electron pressure as well as 79 per cent. of the original pressure of radiation to be made good by the atoms. As there are about 95 electrons to each atom, this means that each atom must exert $\frac{32}{68} \times 95$, or about 45 times the average pressure exerted by an electron, in addition to its share of the deficiency in the pressure of radiation. Thus each atom must exert more than 45 times the pressure it would exert if Boyle's law were obeyed.

To exert such pressures the atoms, or rather their effective volumes, must be so closely packed as to be almost in contact, and the matter may properly be described as being in the liquid state.

8. The total rate of generation of energy inside a sphere of radius r surrounding the centre of a star is $\frac{4}{3}\pi r^3\overline{\rho G}$ where $\overline{\rho G}$ is the mean, by volume, of ρG, the rate of generation of energy per unit volume. This must be equal to $4\pi r^2 H$, the total flux of radiation across the surface of the sphere, so that

$$H = \tfrac{1}{3}r\overline{\rho G}.$$

Introducing the value of H from equation (7), we obtain

$$\frac{d}{dr}(T^{7\cdot5}) = -\frac{rN\rho^2}{3C'}\overline{\rho G},$$

whence, by integration from the centre of a star to a radial distance r, we obtain

$$T^{7\cdot5} = T_c^{7\cdot5} - \frac{N}{3C'}\int_0^r \rho^2\overline{\rho G}r\,dr \quad . \quad . \quad . \quad (9)$$

where T_c is the central temperature of the star.

Extending the integration to the surface of the star, and neglecting the surface-temperature in comparison with the central temperature, this becomes

$$T_c^{7\cdot5} = \frac{N}{3C'}\int_0^R \rho^2\overline{\rho G}r\,dr \quad . \quad . \quad . \quad (10)$$

9. For Sirius B, ρ is about 40,000 times as large as for the sun, R about 0·03 times as large, and $\overline{G}$ about 0·004 times as large. Formula (10) now shows that $T_c^{7\cdot5}$ is about 75,000,000 times as large for Sirius B as for the sun.

The value of T_c for the sun, calculated on the supposition that the sun is purely gaseous, is about 58 million degrees. In the actual sun, in accordance with § 7, T_c will be about 0·68 times this or 38 million degrees, giving a temperature of over 400 million degrees for the centre of Sirius B.

These calculations assume the distribution of density in the sun and in Sirius B to be similar to that in the ideal gaseous sun, and so are no doubt substantially in error, but the general formula (10) shows that in any case the temperatures at the centres of the white dwarfs must be exceedingly high. For o_2 Eridani B, and probably also for Van Maanen's star and Procyon B, the central temperatures come out considerably higher than that just calculated for Sirius B.

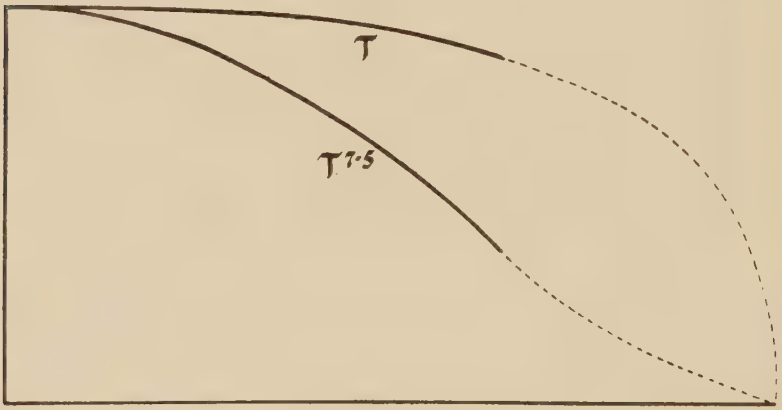


FIG. 1.

10. Let us simplify the problem by supposing that the atoms are packed approximately as closely as they will go inside a sphere of radius r, so that ρ has a uniform value up to a distance r from the centre of the star. Let us further suppose that G is uniform up to this distance. Equation (9) then takes the simpler form

$$T^{7\cdot5} = T_c^{7\cdot5} - \frac{N}{6C'}\rho^3 G r^2 \quad . \quad . \quad . \quad (11)$$

When we plot $T^{7\cdot5}$ against r, as in fig. 1, the graph is a parabola. When we plot T against r, the graph is a very flat curve indeed, the flatness being, of course, a consequence of the comparative largeness of the index 7·5.

The flatness of the graph for T suggests that it is a permissible approximation to treat T as constant up to such distances from the centre as include a large part at least of the star's mass. To an approximation we may regard a liquid star as formed of two distinct parts. The inner part, or core, contains the main mass of the star, and through-

out this the density and temperature, and as a consequence the state of ionisation, are approximately uniform. The outer part, or atmosphere, contains only a small part of the star's mass, and is characterised by a rapidly falling temperature and density.

When a liquid star divides by fission, the dynamical processes are almost completely determined by the core, which behaves approximately like a mass of incompressible fluid. The atmosphere merely veils the essential processes occurring within ; its importance is almost wholly optical and hardly at all dynamical.

11. The result just obtained, that the density, temperature, and ionisation are fairly uniform throughout the central regions of a star, justifies us in treating the centre of the star as representative of all the parts which are dynamically important. The degree of ionisation is determined by the formula of R. H. Fowler used in the previous paper, namely,

$$\log\left(\frac{x}{1-x}\rho\right) = -\frac{69000\mathrm{N}^2}{\mathrm{T}(\tau+1)^2} + \tfrac{3}{2}\log\mathrm{T} + \log(\tfrac{1}{4}\mu\sigma) - 7{\cdot}790 \qquad (12)$$

in which x is the proportion of atoms ionised down to their τ-quantum rings of electrons, and all logarithms are to base 10.

While we must not assume the gas-laws to be obeyed, we wish to obtain results which admit of ready comparison with those for a perfect gas. Let us define λ by the equation

$$\frac{\mathrm{R}}{m\mu}\rho\mathrm{T} = \tfrac{1}{3}a\lambda\mathrm{T}^4 \qquad . \qquad . \qquad . \qquad . \qquad (13)$$

When the gas-laws are obeyed, λ becomes the ordinary ratio of gas pressure to pressure of radiation, which depends almost solely on the mass of the star. When the gas-laws begin to fail, λ decreases, and in the final ideal state in which ρ remains constant through the atoms being packed as closely as they will go, λ varies as $1/\mathrm{T}^3$. Thus as the deviations from the gas-laws steadily increase, $d\lambda/d\mathrm{T}$ ranges between the values

$$\frac{d\lambda}{d\mathrm{T}} = 0 \qquad \text{and} \qquad \frac{d\lambda}{d\mathrm{T}} = -\frac{3\lambda}{\mathrm{T}} \qquad . \qquad . \qquad (14)$$

On eliminating ρ from equations (12) and (13), we obtain

$$1 - x = \frac{1}{1 + 10^{\phi}} \qquad . \qquad . \qquad . \qquad . \qquad (15)$$

where

$$\phi = -\frac{69000\mathrm{N}^2}{\mathrm{T}(\tau+1)^2} - \tfrac{3}{2}\log\mathrm{T} + \log\left(\frac{\sigma}{4\lambda}\right) + 14{\cdot}721 \qquad . \qquad (16)$$

So long as λ remains finite this equation shows that x, the proportion of ionised atoms, is zero at $\mathrm{T} = 0$ and at $\mathrm{T} = \infty$. It is zero when $\mathrm{T} = 0$, because the quanta have not sufficient energy to ionise the atoms ; it is zero at $\mathrm{T} = \infty$ because the number of quanta per atom is zero.

12. From equations (13) and (15) we find

$$\log[(1-x)\rho] = 3\log T + \log(\lambda\mu) - 22{\cdot}511 - \log(1+10^{\phi}) \quad (17)$$

Here $(1-x)\rho$ is the quantity which measures the deviations from Boyle's law, being proportional to the b of Van der Waals' equation. So long as λ remains finite we see that $(1-x)\rho$ increases from 0 to ∞ as T increases from 0 to ∞, but in an actual star a limit would be set to $(1-x)\rho$ because λ would decrease as $1/T^3$ before the limit $T = \infty$ was reached.

As in the previous paper we may conveniently study the changes in $(1-x)\rho$ by examining its maxima and minima.

Disregarding the small variations in μ, differentiation of equation (17) with respect to T gives

$$\frac{d}{dT}\log[(1-x)\rho] = \left(\frac{1}{\lambda}\frac{d\lambda}{dT} + \frac{3}{T}\right)0{\cdot}4343 - \frac{10^{\phi}}{1+10^{\phi}}\left[\frac{69000N^2}{T^2(\tau+1)^2} - \left(\frac{3}{2T} + \frac{1}{\lambda}\frac{d\lambda}{dT}\right)0{\cdot}4343\right] \quad (18)$$

and maxima or minima occur when the right-hand member vanishes. Putting

$$y = \frac{53100N^2}{T(\tau+1)^2} \quad . \quad . \quad . \quad . \quad (19)$$

and restoring the value for ϕ from equation (16), we find that the temperatures T at which maxima and minima occur are given by

$$y^{\frac{3}{2}}\left(y - \tfrac{3}{2} - \frac{2T}{3\lambda}\frac{d\lambda}{dT}\right)10^{7{\cdot}635-1{\cdot}303y} = \frac{4\lambda N^3}{\sigma(\tau+1)^3}\left(1 + \frac{T}{3\lambda}\frac{d\lambda}{dT}\right) \quad (20)$$

13. Within ranges of temperature and density in which the gas-laws are nearly obeyed we may neglect $d\lambda/dT$, and the equation reduces to

$$y^{\frac{3}{2}}(y - \tfrac{3}{2})10^{7{\cdot}635-1{\cdot}303y} = \frac{4\lambda N^3}{\sigma(\tau+1)^3} \quad . \quad . \quad (21)$$

The right-hand member does not involve the temperature. The left-hand member is a function of y only, which is positive only in the range from $y = \frac{3}{2}$ to $y = \infty$. It is readily found that within this range its value never exceeds $1{\cdot}52 \times 10^5$, a value which it attains when $y = 1{\cdot}95$.

Thus equation (21) has no roots at all if

$$\frac{4\lambda N^3}{\sigma(\tau+1)^3} > 1{\cdot}52 \times 10^5 \, . \quad . \quad . \quad . \quad (22)$$

and in this case $(1-x)\rho$ increases steadily from 0 at T = 0 until the gas-laws fail.

On the other hand, if

$$\frac{4\lambda N^3}{\sigma(\tau+1)^3} < 1{\cdot}52 \times 10^5 \, . \quad . \quad . \quad . \quad (23)$$

equation (21) has two roots in y, one being less than $y = 1{\cdot}95$ and the other greater. As T increases from 0 to ∞, $(1 - x)\rho$ starts by increasing but reaches a maximum for some value of y between ∞ and 1·95; after this it decreases, reaching a minimum for some value of y between 1·50 and 1·95, after which it steadily increases.

When λ is such that inequality (23) is only just satisfied, the minimum of $(1 - x)\rho$ occurs when $y = 1{\cdot}95$, or, restoring its value for y, when

$$\mathrm{T}(\tau + 1)^2 = 27{,}200\mathrm{N}^2 \quad . \quad . \quad . \quad (24)$$

As we pass to smaller values of λ (*i.e.* stars of greater mass), the value of y decreases towards $y = 1{\cdot}50$, and in the limiting case of a star of very great mass, the minimum of $(1 - x)\rho$ occurs when

$$\mathrm{T}(\tau + 1)^2 = 35{,}400\mathrm{N}^2 \quad . \quad . \quad . \quad (25)$$

14. The foregoing analysis confirms and amplifies the results which were obtained, by a very rough approximation, in the earlier paper. We see that as a star contracts along a series of equilibrium configurations, keeping its mass constant, the deviations from the gas-laws will, in general, wax and wane as successive rings of electrons undergo ionisation. Equations (24) and (25) give the critical temperatures, in two limiting cases, at which the minimum deviations from the gas-laws occur, these being calculated on the supposition that *at these minima* the deviations from the gas-laws are slight, while equation (23) expresses the condition that such minima shall occur.

In general, the value of T in a configuration of minimum deviation from the gas-laws has a value intermediate between the two limits specified by equations (24) and (25). If we disregard the comparatively small difference between these limits, we return to the approximation of the earlier paper which regarded the temperature of minimum deviation as having a uniform value, independent of the mass of the star. The more careful analysis of § 12 has shown that actually this temperature increases with increasing stellar mass, although only slightly. This accords, as we shall see, with the fact that the calculated central temperatures for massive main-sequence stars are somewhat greater than those for stars of small mass.

The general result we have obtained may be represented graphically in fig. 2, in which the ordinate $(1 - x)\rho$ represents the measure of deviations from Boyle's law, or the extent to which the atoms are jammed together in the central regions of the star, while the abscissa represents the temperature of those central regions, low temperatures lying on the right.

So long as we limit our attention to the ionisation of one definite ring of electrons, and assume equation (23) to be satisfied, the graph of $(1 - x)\rho$ is a curve such as OABC, B representing the minimum. Along the branch BC the jamming of the atoms, which we may suppose to have been slight at B, continually increases until the gas-laws fail entirely, and our analysis with them.

To adjust for deviations from the gas-laws we must depress the value of ρ corresponding to a given value of T. By equation (13) this decreases

λ, and this in turn, by equation (17), depresses the value of $(1-x)\rho$. Thus the curve BC must be replaced by a lower curve BP. But before this has proceeded far, the ionisation of the next inner ring of electrons may become of importance, depressing the curve still further. If it depresses it so far that the deviations from the gas-laws become slight, and if also inequality (23) is satisfied for the new ring of electrons, the curve will follow a new ionisation curve A′B′C′ similar to the original ionisation curve ABC, but shifted to a region of higher temperature, a minimum of jamming now occurring at B′. Similar fluctuations repeat themselves for each successive ionisation until a ring of electrons is reached for which τ and σ are so small that condition (23) is no longer satisfied. The value of $(1-x)\rho$ does not now pass through a further minimum, but continually increases, approaching asymptotically to

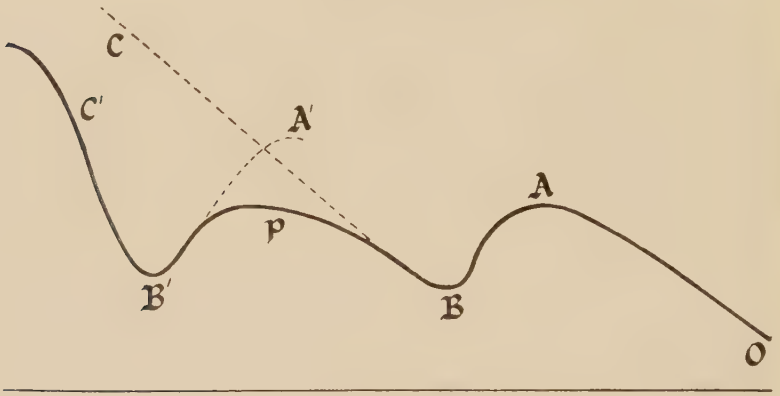


FIG. 2.

values of $(1-x)\rho$ which represents atoms packed as close as they will go.

For the M-ring, $\tau+1=3$ and $\sigma=8$, so that, from condition (23), M-ring ionisation gives rise to a definite minimum if $\lambda N^3<8{\cdot}2\times10^6$. With $N=95$ this gives a minimum if $\lambda<9{\cdot}6$, a condition which requires the star to be considerably more massive than the sun.

For the L-ring, $\tau+1=2$ and $\sigma=8$. The condition that a minimum of jamming shall occur is that $\lambda N^3<2{\cdot}4\times10^6$. With $N=95$ there is a minimum if $\lambda<2{\cdot}9$, and so only for stars more massive than Sirius (for Sirius A, $\lambda=3{\cdot}1$).

Finally for the K-ring, $\tau+1=1$ and $\sigma=2$, so that there is a minimum of jamming if $\lambda N^3<7{\cdot}6\times10^4$. With $N=95$ the condition becomes $\lambda<0{\cdot}09$, which is far from being satisfied even by the most massive of stars. Thus there can be no minimum jamming produced by K-ring ionisation, at any rate until after our present approximations have failed through deviations from the gas-laws becoming excessive.

15. Let us next examine conditions when the deviations from the

gas-laws are excessive, returning for this purpose to the quite general equation of § 12, namely,

$$y^{\frac{3}{2}}\left(y - \tfrac{3}{2} - \frac{2\mathrm{T}}{3\lambda}\frac{d\lambda}{d\mathrm{T}}\right)10^{7\cdot635-1\cdot303y} = \frac{4\lambda\mathrm{N}^3}{\sigma(\tau+1)^3}\left(1 + \frac{\mathrm{T}}{3\lambda}\frac{d\lambda}{d\mathrm{T}}\right). \quad (26)$$

The deviations from the gas-laws are represented by the presence of the two terms in $d\lambda/d\mathrm{T}$, a quantity which, as we have seen, varies from 0 to $-3\lambda/\mathrm{T}$ as the deviations from the gas-laws increase.

The term in $d\lambda/d\mathrm{T}$ makes no essential difference to the character of the function on the left hand of this equation. The range within which it is positive is no longer from $y = \infty$ to $y = \frac{3}{2}$, but from $y = \infty$ to $y = \mathrm{Q}$, where Q is the algebraically greater of the quantities 0 and $\frac{3}{2} + \frac{2\mathrm{T}}{3\lambda}\frac{d\lambda}{d\mathrm{T}}$. Since $\frac{d\lambda}{d\mathrm{T}}$ becomes equal to $-3\lambda/\mathrm{T}$ before $y = 0$, we see that in general 0 is the algebraically greater, and that the quantity on the left of equation (26) is positive from $y = 0$ to $y = \infty$. There is a possibility (which is unimportant) that the quantity may become negative over a small range. Near $y = 0$, the graph of the function is a semi-cubical parabola.

On the other hand, the term in $d\lambda/d\mathrm{T}$ profoundly modifies the right-hand member of equation (26). To allow for its presence we must replace our former λ by

$$\lambda + \tfrac{1}{3}\mathrm{T}\frac{d\lambda}{d\mathrm{T}}. \quad . \quad . \quad . \quad . \quad . \quad (27)$$

which, as equation (13) shows, is proportional to

$$\frac{1}{\mathrm{T}^2}\frac{d\rho}{d\mathrm{T}}$$

and this becomes small beyond limit as we approach configurations in which the atoms are closely jammed together.

As a consequence, equation (26) always has at least one pair of roots, and the degree of jamming always passes through one minimum and maximum. The further λ is below the critical value for λ given by inequality (23), the greater the value of $d\lambda/d\mathrm{T}$ must be before the root occurs, and so the greater must be the deviations from the gas-laws.

The important case is K-ring ionisation, and to a rough approximation we may suppose that the maximum (the first root) occurs when expression (27) has the critical value 0·09 calculated in § 13, so that

$$\frac{d\lambda}{d\mathrm{T}} = -\frac{3(\lambda - 0\cdot09)}{\mathrm{T}}.$$

For all ordinary stars λ is very large compared with 0·09, so that $d\lambda/d\mathrm{T}$ has almost its limiting value $-3\lambda/\mathrm{T}$, which occurs when the atoms are packed as closely as they will go. Just before the closest packing occurs our analysis has shown that $(1-x)\rho$ passes through a maximum and starts decreasing. This relieves the jamming and the star is now free to contract further with still increasing temperature until the jamming passes through a minimum, with the K-ring largely

ionised and the atoms accordingly stripped bare to their nuclei. After this (or possibly after a succession of minima and maxima) the jamming again increases and ends by increasing without limit, the final condition being one in which bare nuclei and a few K-ring atoms are packed as closely as they will go.

16. We have seen that the condition that any configuration shall be dynamically stable is that

$$\frac{dE}{dR} > \frac{dG}{dR} \cdot \quad . \quad . \quad . \quad . \quad . \quad (28)$$

in which the right-hand side is generally positive, but so small that it may be neglected.

When the opacity is given by Kramers' law, it is readily found that $E \propto R^{-\frac{1}{2}}$. Equation (28) now shows, as has already been found, that all

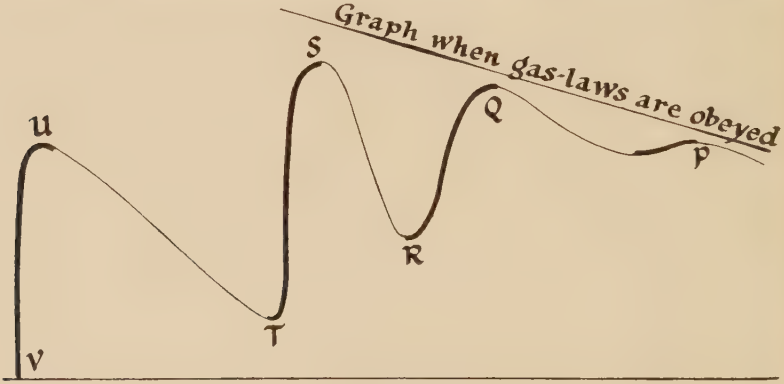


FIG. 3.

configurations in which the gas-laws are obeyed are unstable. We have seen that we can pass from such a configuration to one of the same radius and mean density in which the gas-laws are not obeyed, by a process of lowering the temperatures throughout. Since E varies as $T^{7\cdot5}$, this lowers the emission E very substantially.

In fig. 3 log E is taken as ordinate and log R as abscissa, so that large values of R are to the right. If the gas-laws are obeyed, the graph of log E is determined directly by the relation $E \propto R^{-\frac{1}{2}}$, and so is a slant line such as is shown at the top of the diagram. We can take account of deviation from the gas-laws by depressing the value of T, and so also of E corresponding to any given radius. The rhythmical fluctuations in the degree of deviation from the gas-laws, which we have found to result from the ionisation of successive rings of electrons, will show themselves by the graph of E hanging in a series of festoons below the straight line which gives the emission when the gas-laws are obeyed. The points of nearest approach to this line are the configurations in which the deviations from the gas-laws are a minimum, and these coincide very approximately with the highest points of the festoons.

Thus the highest points of the festoons are determined (*cf.* equations (24) and (25)) very approximately by

$$T(\tau + 1)^2 = QN^2 \quad . \quad . \quad . \quad . \quad (29)$$

where Q has a value intermediate between 27,200 and 35,400 according to the mass of the star, the higher values of Q being appropriate to stars of higher mass.

We obtain a curve such as PQRSTUV. The parts of the curve for which dE/dR is positive are drawn thick. They represent the stable configurations so long as dG/dR is neglected, but when dG/dR is taken into account, the ranges of stability become somewhat more restricted. The long nearly vertical range ST represents configurations in which the temperature T and emission E steadily diminish, while R has an almost constant value as a consequence of K-ring atoms being packed almost as closely as they will go. We have seen that this range approaches a minimum value of R very closely and for a long time, until just before contact occurs the K-ring begins to dissolve and the jamming is relieved. Ultimately the vertical range UV represents a jamming of nuclei and a few K-rings from which there is no relief.

Strictly speaking, a range such as ST ought not to be drawn quite vertical, since a decrease of emission is associated with a decrease of temperature which would decrease the ionisation if ρ were kept constant. But a simple calculation based on the equations of § 10 shows that this effect is inappreciable ; I find that halving the temperature (reducing the emission by 5·6 mags.) makes a change of well under 1 per cent. in x.

17. In fig. 3 log E and log R were used as co-ordinates, but we might equally well have taken log E (or 0·4 × abs. bol. mag.) and log T_e (where T_e is effective temperature) as co-ordinates, and so have exhibited our results in a diagram which is very similar to the ordinary Russell diagram. The transformation between the two sets of co-ordinates is effected by the equation

$$E = 4\pi\sigma R^2 T_e^4.$$

This gives at once

$$\log E = 4 \log T_e + 2 \log R + \log (4\pi\sigma),$$

so that when log E and log T_e are used as co-ordinates, all stars of a specified radius lie on a straight slant line, the lines R = constant being all parallel, equal distances representing equal differences in log R.

If curves such as those shown in fig. 3 are transferred to such a diagram, we obtain curves of the general type shown in fig. 4, in which stable configurations are again drawn thick. We see at once that the range of stable configurations is of the same general nature as the range occupied by stars in the Russell diagram, and by adjusting the constants at our disposal the two ranges can be made to coincide almost exactly, as has to some extent been done in fig. 4.

The most marked feature in both diagrams is the marked congestion at the left-hand edge of the main sequence. Our theory interprets the main sequence as consisting of stars in which stability is produced by a jamming of K-ring atoms ; the great congestion on its left-hand edge arises from stars having to stay so long on the main sequence before

B
A
F
G (giant)
K
M
-4
-2
0
+2
+4
+6
+8
+10
M-ring ionised
L-ring ionised
L-ring congestion
K-ring congestion
K-ring ionised
Deviations from gas-laws small
Congestion of Mixed atoms
White Dwarfs
log Te

FIG. 4.

reaching the very high degree of jamming at which the K-ring begins to dissolve.

So long as we confine ourselves to a small area of the diagram, the time a star needs to traverse a small range of its path is proportional to dE or to d(log E), which is proportional to the projection of the bit of path on the vertical. Thus stars run very rapidly along their path when this is nearly horizontal, but very slowly over ranges of path, such as those through the main sequence, which are inclined at a high angle to the horizontal.

The position of the main sequence is most easily fixed by equation (29). As we have seen, this approximately determines the position of the right-hand edge of the main sequence when $\tau + 1$ is put equal to 2 and Q is given a somewhat uncertain value between 27,200 and 35,400.

The next most marked feature is the giant branch which, joining the main sequence, gives the whole figure its characteristic reversed-γ appearance. The inner fork of the branch can be fixed with some precision observationally, and its position in our diagram is determined by the condition that the two sides of inequality (23) shall be just equal, or that

$$4\lambda N^3 = 1{\cdot}52 \times 10^5 \sigma(\tau + 1)^3 \quad . \quad . \quad . \quad (30)$$

Observationally, the inner fork is found to occur at about abs. mag. + 1 and spectral type A5. Here λ is about 3, and on inserting the appropriate values $\tau + 1 = 2$ and $\sigma = 8$, we find

$$N = 93{\cdot}2 \quad . \quad . \quad . \quad . \quad (31)$$

At this particular point, the value which must be assigned to Q in equation (29) is Q = 27,200, while the value of T at this point is about 60,000,000. Inserting these values equation (29) gives

$$N = 93{\cdot}9 \quad . \quad . \quad . \quad . \quad (32)$$

It is not, of course, claimed that N can be determined with the accuracy suggested by these two values, but I cannot but think it significant that the atomic numbers come reasonably close to that of uranium. We could have determined N in the same way, but with less accuracy, from any other point on the main sequence. The calculated values for N are found to increase as we pass to more massive stars. This is, of course, in accordance with the view that the most massive elements have the highest capacity for generating energy and so disappear first as the star ages, with the result that the average atomic weight in a star continually decreases.

18. Elsewhere I have calculated the central densities of various stars on the supposition that the stars are in the gaseous state throughout.* For main-sequence stars the central densities are found to be some hundreds, while for giants such as α Orionis and Capella A they are comparable with unity. It is difficult to know by how much these densities must be altered when the stars are supposed liquid. If we suppose the central density to have about the same value in a liquid star as that calculated for a gaseous star, we can find the effective

* *M.N.*, **87**, 40 (1926).

volumes of the stellar atoms ionised down to their K- and L-rings from our knowledge of the extent of the deviations from the gas-laws. The diameters so obtained come out some 50 to 80 times the diameters of the electron orbits as calculated from Bohr's theory. This is perhaps not surprising. Even with neutral helium the effective diameter of the atoms in the liquid state is 7·4 times that of the electron orbits as calculated from Bohr's theory. No one can say what it would be if the temperature were raised from two or three degrees absolute to ten or a hundred million degrees absolute, and we might, in any case, expect atoms surrounded by a powerful electric field to have relatively larger effective diameters than neutral atoms such as that of helium.

The tentative hypothesis which I have found best to fit the facts is that the effective diameters are far larger than the diameters of the electron orbits predicted by Bohr's theory, and that the central densities of the stars are far less than those calculated on the supposition that the stars are gaseous, so that the region of high density extends quite a long distance away from the centre of the star. Some such hypothesis seems to be necessary to explain the observed facts of fission as well as for other reasons.

We now pass to consider problems of stellar evolution in the light of the new concepts we have attained.

Long-period Variables.

19. A star is first born out of a nebula with a density so low that it is in the gaseous state throughout, the gas-laws being completely obeyed. For this reason it is dynamically unstable, and must contract until there are substantial deviations from the gas-laws in its central regions.

The equations of motion given in the previous paper enable us to follow out its motion during the period of instability. We return to the model in which pressure and density are connected by the fictitious law $p \propto \rho^{1+s}\mathrm{T}$, this reducing to the ordinary gas-laws when $s = 0$. We may disregard any dependence of the rate of generation of energy on temperature and density, and so put $\alpha = \beta = 0$. Equation (8) of the previous paper * now becomes

$$\mathrm{C}_v\frac{d^3}{dt^3}(\delta r) + \frac{(7+n)\mathrm{G}_0}{\mathrm{T}_0}\frac{d^2}{dt^2}(\delta r) + \frac{\gamma \mathrm{M}_r}{{r_0}^3}\left[\frac{\lambda+4}{\lambda+1}\left(\frac{3p}{\rho \mathrm{T}_0} - \mathrm{C}_v\right) + \frac{3s\mathrm{C}_v\lambda}{\lambda+1}\right]\frac{d}{dt}(\delta r)$$
$$+ \frac{\gamma \mathrm{M}_r}{{r_0}^3}\frac{\mathrm{G}_0}{\mathrm{T}_0}\left[-n\frac{\lambda+4}{\lambda+1} + 3s(7+n)\frac{\lambda}{\lambda+1}\right](\delta r) = 0 \quad . \quad (33)$$

The first two terms in this are necessarily positive. The last two terms contain the factor $\gamma \mathrm{M}_r/{r_0}^3$, which, as a matter of simple calculation, is easily found to be large in comparison with $\mathrm{G}_0/\mathrm{T}_0\mathrm{C}_v$.

It follows that if we imagine equation (33) split up in the form

$$\mathrm{C}_v\left[\frac{d^2}{dt^2} + 2\mathrm{P}\frac{d}{dt} + \mathrm{Q}\right]\left[\frac{d}{dt} + \epsilon\right](\delta r) = 0 \quad . \quad . \quad (34)$$

the value of Q will in general be large in comparison with P and ϵ.

* *M.N.*, **87**, 404 (1927).

So long as the star remains of such low density that the gas-laws are approximately obeyed, s will be small and the last two coefficients in equation (33) are negative. Thus Q is negative and large, while ϵ is positive. The time-factors of the possible oscillations of the star are

$$e^{-Pt\pm(P^2-Q)^{\frac{1}{2}}t},\ e^{-\epsilon t}$$

and we see that the value of δr will increase exponentially with a modulus $(P^2 - Q)^{\frac{1}{2}} - P$. Since $-Q$ is large compared with P and is comparable with $\gamma M_r/r_0^3$ or $\gamma\rho$, we see that this modulus is comparable with $(\gamma\rho)^{\frac{1}{2}}$. This shows that the star will contract with extreme rapidity, its radius diminishing to $1/e$ times its value in a period comparable with $(\gamma\rho)^{-\frac{1}{2}}$, which is of the order of hundreds of days. Thus a few years suffice for such a contraction that the gas-laws begin to fail, after which the motion alters its character.

As the deviation from the gas-laws begins to be important, s steadily increases and finally attains such a value that the last term in equation (33) vanishes and subsequently becomes positive. This brings us to the case already discussed in the previous paper. We saw there that when s is so large that the last term in equation (33) is positive, contractional instability disappears, and the two other roots of equation (34) represent pulsational vibrations which may be either stable or unstable.

Equation (15) shows that the vibrations will be stable if

$$-n<\left(7-\frac{7}{3(\gamma-1)(1+\xi)}-\frac{21}{\lambda}\right)\frac{\lambda}{\lambda+1} \quad . \quad . \quad (35)$$

but will otherwise be unstable. Here $(1 + \xi)$ is a factor representing deviation from the gas-laws. If we disregard $1 + \xi$, and put $n = \frac{1}{2}$ (Kramers' law) and $\gamma = 1\frac{2}{3}$ (monatomic gas), the condition for stability requires that $\lambda>5$. If $\lambda<5$, as is the case with stars of mass greater than about $2\odot$, the pulsations will be unstable.

This unstable pulsation, of course, merely represents the original unstable contraction in a new guise. The period of the pulsation is now comparable with $(\gamma\rho)^{-\frac{1}{2}}$, which is hundreds of days, while the modulus of increase is of the order of $C_v T/G$, which is millions of years. Thus the amplitude only increases slowly. Our discussion, which has left viscosity out of account, indicates that the amplitude of pulsation would increase beyond limit, but viscosity will keep the amplitude in check and the star may be expected to pulsate, with a large but approximately constant amplitude, in a period of some hundreds of days. This exactly describes the behaviour of long-period variables.

The limit of mass ($\lambda = 5$) below which pulsations are rapidly damped out has been determined only by disregarding deviation from Boyle's law. If the deviations from Boyle's law are extreme, the value of $1 + \xi$ becomes very great and the limit is found to be $\lambda = 2{\cdot}7$, representing a star of mass about four times that of the sun. The critical mass must therefore lie somewhere between the limits $2\odot$ and $4\odot$. Stars whose mass lies below this limit are not liable to unstable pulsations, and so cannot ever function as long-period variables. As regards stars

with masses above this limit, the pulsations of the stars of smaller mass will die away first as the deviations from the gas-laws increase.

Stellar Evolution.

20. We have seen that when a star is born as a mass of gas of nebular density, the first event in its life is a rapid contraction, occupying only a few years, until the deviations from the gas-laws become so great that it is immune from further contraction resulting from mere dynamical instability.

If the star's mass is large, its rapid contraction will merely be transformed into pulsations of a few hundred days' period, and the star begins its proper stellar life as a long-period variable. On the other hand, if its mass is only moderate, such pulsations are at once damped out and the star starts as a normal non-variable star.

In either event, the star's further evolution is determined by the fundamental equation for the transformation of matter into radiation, namely,

$$\frac{dM}{dt} = -\frac{E}{C^2}$$

in conjunction with a further equation giving E in terms of the time. If the rate of generation of energy is supposed to be entirely independent of the density, pressure, and state of ionisation, this equation will be of the purely radio-active type,

$$E = A_1 e^{-\kappa_1 t} + A_2 e^{-\kappa_2 t} + \ldots$$

although no doubt such an equation only provides a very rough approximation to the actual facts.

The star picks its way from one configuration to another by steps in dM and dE which conform to these equations. If it comes in time to a configuration beyond which no further stable configuration exists, it must pass through a series of unstable configurations, either cataclysmically or by slow contraction or expansion until it comes to configurations which are again stable.

After a succession of such drops from one region of stability to another, it is likely to find itself on the main sequence. Alternatively, as I have shown,* the process of fission may divide it into two constituent stars and place each of these on the main sequence at once.

The star moves gradually down the main sequence, contracting all the while and increasing its central density and temperature until its atoms, which are now mostly ionised down to their K-rings, are so closely packed that the density can barely increase any further. Just before this last stage is reached, the K-rings of the atoms begin to be ionised and the star is free to contract further. After passing through a succession of unstable configuration it ends stably as a white dwarf. It is slightly disconcerting to notice that our sun is perilously near to the dangerous left-hand edge of the main sequence, so that its collapse into a feebly-luminous white dwarf may start at any instant.

* *M.N.*, **85**, 797 (1925).

The white dwarf state is final. No further ionisation or contraction is possible. Moreover, on account of the last ring of electrons now being ionised, the radiation is very slight and the loss of mass consequently very slight. The star is in an almost stagnant state in which changes of mass and of luminosity are hardly appreciable within periods comparable with the whole lives of ordinary stars. In the time-interval necessary to change Plaskett's star into a star like the sun, Sirius B will lose 0·15 per cent. of its present mass.

This state of complete ionisation provides a sort of " cold-storage " —if the metaphor is not too inappropriate to a temperature of about a thousand million degrees—in which stellar atoms, no matter how great their normal generating capacity, are preserved from decay. This concept may have profound cosmogonical consequences, since the matter at the centres of the spiral nebulæ must in all probability be fully ionised and so immune from decay. Possibly the nuclei of the spiral nebulæ constitute vast storehouses of such matter which only begins to undergo annihilation and to emit radiation when it is first formed into stars. The life of Plaskett's star, as a star, can hardly have been more than some 10^{11} years, but the atoms of which it is composed may have previously lived an infinitely longer life, completely ionised at the centre of a nebula, and therefore stagnant and immune from annihilation. As a corollary, it would be difficult to deny that all the matter of the universe may have been created at the same instant.

Multiplets of the Nickel and Cobalt Arc Spectra in the Chromospheric Spectrum. By C. R. Davidson and F. J. M. Stratton, D.S.O., M.A.

(a) *Nickel.*—In the Report on the Total Solar Eclipse of 1926 January 14 (*Mem. R.A.S.*, **64**, 133, 1927), we have given a list of 34 unclassified lines of nickel appearing in the chromospheric spectrum between 3100A and 4000A. A comparison with an analysis of the nickel arc spectrum into multiplets by Bechert and Sommer (*Ann. d. Phys.*, **77**, 351, 537, 1925) shows that in the range considered practically every line in the arc spectrum of nickel arising from two terms with the serial number one is present in the chromosphere, while only one line arising from the higher energy levels associated with the serial number two is present. In all 80 lines are probably present in the spectrum, though many are involved in blends, and 15 of the additional identifications with nickel are free from blends. Some of these lines had been previously identified by Mitchell with weak nickel lines, but in the absence of corroborative evidence, such as comes from the multiplets, we had left them in our *Memoir* as unidentified. Only one line of the 34 we had identified with nickel is not absorbed into the arc multiplets. This line is 3769·47A (arc 1, spark 5), which may belong to the ionised atom. It may be noted that one multiplet $1^3D' - 1^3F'$, reasonably strong in our spectrum, is missing in Mitchell's spectrum.

The grouping of the lines into multiplets is given below. The lines not identified with nickel in the *Memoir* are marked with a +. Brackets indicate that the line is mainly due to another element.

Nickel (28).

λ.	Intensity. Arc.	Intensity. Spark.	Chromosphere. λ.	Chromosphere. Intensity. 1926.	Chromosphere. Intensity. 1905.	Blends. λ.		Blends. Intensity. Arc.	Blends. Intensity. Spark.
				Ni $1^1D'-1^1P'$.					
3380·58	10*u*	6	(·30	5	3)	*Ti*+	·28	5	15
				$1^1D'-1^3P'$.					
3831·68	5	2	(2·33	15	30)	*Mg*	2·31	50	300
+3973·53	4	2	(·50	4	5)				
				$1^3D'-1^3P'$.					
3492·96	30	10	·92	3	1				
3510·34	15	10	·33	1	1				
3524·54	50	15	·52	5	3				
3597·70	10	6	·73	1	1				
3610·46	10	4	·36	2	2N	*Cd*	·51	500	100
+3722·55	5	2	·51	3	2	*Fe*	·57	20	6
				$1^3F-1^1P'$.					
+3249·44	3	1	·40	1		*La*	·35	4	3
				$1^3F-1^3P'$.					
3664·09	4	2		—	—	Between H_{28} and H_{29}			
+3670·42	4	2	·45	—	1				
+3793·66	3	1	·75	1	1				
				1^3D-1^1D.					
+3200·43	3	1	(·23	2	)	*Y*+	·26	10	10
+3271·12	4	2	(·11	4	)	*V*	·11	2	10*u*
+3362·69	2	1	·81	1	—				
				$1^1D'-1^1D$.					
3566·38	20	10	·42	2	—				
				$1^1D'-1^3D$.					
+3634·94	2	1	(5·29	1	1*d*)				
3775·57	8	5	·59	2	3				
3807·15	8	5	·35	1	2	*Fe*	·54	3	2

Nickel (28).—*continued.*

λ.	Intensity. Arc.	Intensity. Spark.	Chromosphere. λ.	Intensity. 1926.	Intensity. 1905.	Blends. λ.		Intensity. Arc.	Intensity. Spark.
				$1^3D'-1^3D$.					
+3328·72	2	—	(·86	—	3)	*Fe*	·85	2	1
+3367·89	3	1	(8·05	10	5)	*Cr*+	·05	3	10
3392·99	20*u*	8	3·12	4	0	*Cr*	·04	1	8
3423·71	10	5	·70	2	0				
3446·26	30*u*	10	·25	4	2				
3472·55	10	5	·60	3	—	(*Ny*	·48	3	3)
						Mn	7·79	10*u*	4
+3548·19	6	3	(·00	2*d*	1)		8·02	10*u*	3
							8·19	3	3
				$1^3D'-1^5D$.					
+3694·07	3	1	(·02	3	4)	*Fe*	·00	4	4
						Ny	·20	100	200

The other lines of this multiplet, some of which should be stronger, are missing, so that this identification is probably not correct.

				$1^1D'-2^3D$.					
+3225·03	6	2	(·47	1	)				
3250·75	5	2	—	—					
3322·32	8	3	·22	1					

Only the strongest line of this multiplet is present.

				1^3F-1^1D.					
3320·26	8	3	·30	0	0				
3420·74	2	1	—	—	—	Mitchell says "many faint lines."			
				1^3F-1^3D.					
3369·58	15*u*	4	·60	2	0				
3483·78	8	4	·64	2	1N	*Zr*	·53	3	7
3500·85	6	4	·88	1	0				
+3527·99	4	1	·80	1	0	*Fe*	·80	3	2
+3612·73	6	3	2·71	—	1	*Zr*+	3·08	4	5
			(3·01	2	—)				
+3641·63	1	1	(·33	5	8)	*Ti*+	·33	3	20
				$1^1D'-1^1F'$.					
3619·39	50	15	·39	3	2				

Nickel (28).—*continued.*

λ.	Intensity. Arc.	Intensity. Spark.	Chromosphere. λ.	Intensity. 1926.	Intensity. 1905.	Blends. λ.		Intensity. Arc.	Intensity. Spark.
				$1^1D'-1^3F'$.					
+3736·81	4	2	(7·00	12	25)	*Ca*+	6·90	20	15
						Fe	7·13	30	8
3783·53	8	5	·56	4	5*d*	Blend with element.		unidentified	
				$1^3D'-1^1F'$					
3243·06	8	3	·06	1					
+3315·67	10	3	(·33	4	)	*Ti*+	·27	2	9
				$1^3D'-1^3F'$.					
+3337·01	1	—	(6·75	2	0)	*Mg*	6·69	10	8
+3374·23	4	2	·29	3	—	*Ti*+	·35	1	4
+3413·99	4	2	·99	1	—				
3452·89	10	5	·88	3	—				
3461·66	20	10	(·63	8*	3)	*Ti*+	·50	3	15
3513·95	5	8	·99	3	1				

The identification of the weakest line of the multiplet, 3337·01, is doubtful.

				$1^3D'-1a^3F'$.					
+3286·95	4	1	(·78	1	)	*Fe*	·76	8	5
+3361·56	6	2	(·25	15	8)	*Ti*+	·22	10	50
3414·77	30*u*	10	·84	4	1				
3433·57	15	6	(·31	10	8)	*Cr*	·29	2	10
3458·47	20	10	·38	3	1*d*				
3515·06	30	10	·00	3	2*d*				
				$1^3D'-2^3F$.					
3101·56	10*u*	4	—	—					
3134·10	30	4	·17	0					

The missing line comes where the spectrum is weakening rapidly in strength.

				$1^3D'-1^5G$.					
+3469·2 (*calculated*)			·38	1	—	*Ni*	·38($1^3F_2-1'F_3'$)		
+3523·45	3	2	·47	1	—	*Ca*	·44	4	5
+3553 57	3	2	·57	1	—				
+3587·93	4	2	·95	1*d*	0				
+3609·31	5	2	·35	—	0				
+3661·94	2	2	(2·24	6	3)	*H*30	·26		
						Ti+	·24	2	15

Nickel (28).—*continued.*

λ.	Intensity. Arc.	Spark.	Chromosphere. λ.	Intensity. 1926.	1905.	Blends. λ.		Intensity. Arc.	Spark.
				$1^3F_3-1^3F_2$.					
+3467·50	4	2	·33	1	0				
				$1^3F-1^1F'$.					
+3221·66	5	2	(·31	1*d*	)				
+3366·17	5	3	·18	3	0	*Ti*+	·20	1	3
+3469·38	5	3	·38	1	—				
				$1^3F-1^3F'$.					
+3350·1	(*calculated*)		—	—	—				
3437·28	8	5	·19	2	1*d*	*Zr*	·14	3	4
+3464·5	(*calculated*)		·48	0	—	*Sr*+	·47	30	100
+3507·69	4	2	·55	1	—				
+3577·21	1	—	(6·88	1	2)	*Zr*+	·85	5	15
+3602·28	5	2	(·49	—	0N)	*Fe*	·49	3	1
+3647·4	(*calculated*)		·39	—	1	*Fe*	·39	1	1

The independent evidence for this multiplet is very weak; its strongest line 3437·28 is probably present.

				$1^3F-1a^3F'$.					
3391·05	10	3	—	—	—				
+3409·58	5	2	(·80	3	2)	*Ti*+	·80	1	4
+3413·55	5	3	·55	0	§	§ Mitchell, "many lines."		fine	
3519·78	4	3	·79	0	2*d*	*Zr*	·60	4	3
+3551·54	3	1	·40	—	1				
3571·87	10	3	·86	1	1				
3688·41	10	4	·47	1	—	*Eu*	·42	20	10

The absence of the strong line 3391·05 is puzzling.

				1^3F-1^3G.					
3145·12	1	1	—	—	—				
+3226·99	4	2	·79	2					
3232·94	10	3	·82	2		*Fe*	·81	—	1
+3282·70	3	2	(·33	4	)	*Ti*+	·33	2	10
+3371·99	6	3	(2·20	3	—)	*Sc*+	2·14	20	10
						Ti+	2·20	2	4
+3380·89	3	2	·80	0	0	*Sr*+	·71	20	80
						La+	·88	8	10

The missing line is a very weak line in the weak part of the spectrum, but the evidence for the whole multiplet is very weak.

(b) *Cobalt.*—A study of the cobalt arc spectrum by Catalan and Bechert (*Ann. d. Phys.*, **77**, 336, 1925) has led to some fresh identifications of cobalt lines in the chromospheric spectrum and to the classification in multiplets of the unclassified lines given in our *Memoir* (*loc. cit.*, p. 133).

We first note a few corrections and additions. In accordance with the notation of Catalan and Bechert, for the multiplet

$$1\,^4F'-1\,^4D' \textit{ read } 2\,^4F-2\,^4D.$$

One fresh line has been provisionally identified (3561·33), the other 4 lines of the multiplet are blended with stronger lines.

For the multiplet

$$1\,^4F'-1\,^4D \textit{ read } 2\,^4F-1\,^4D.$$

This multiplet is missing from the 1926 flash though present in 1905. One of the weaker lines at 3974·73 may be present in 3974·54 (2), but in view of the absence of the stronger lines this identification cannot be made.

An additional identification can be made in the multiplet $1\,^4F-1\,^4D$, namely, the line 3552·89. The two other lines of the multiplet 3491·32, 3584·80 are blended with strong lines of Ti^+ and Y^+ respectively.

One more identification can be made in $1\,^4F-1\,^4G$, namely, 3456·94 (blended with *V*), the other lines of the multiplet are too weak to show or are lost in strong blends.

The multiplet

$$1\,^4F-1\,^4F'' \textit{ should read } 1\,^4F-1\,^4F',$$

the remaining 5 lines of this multiplet are lost in strong blends or are too weak to be seen.

Fresh multiplets identified as present are given below.

Cobalt (27).

λ.	Intensity. Arc.	Intensity. Spark.	Chromosphere. λ.	Intensity. 1926.	Intensity. 1905.	Blends. λ.		Intensity. Arc.	Intensity. Spark.
				Co $2\,^4F-2\,^4G$.					
3367·11	5	3	—	—	—				
+3385·23	4	4	(·03	2	0)				
3443·65	15	6	·85	1	2	*Fe*	·88	15	5
3449·17	10	5	·38	1	0				
3449·45	10	5							
3453·51	20	10	·56	2	0				
3495·68	5	5	(·34	1	2*d*)	*Cr*	·40	1	4
			(·79	4	2)	*Mn*+	·84	1	6
+3509·84	8	5	·87	1	1	*Ti*+	·85	1	3
3529·81	15	6	·75	1	1				

Cobalt (27).—*continued.*

λ.	Intensity. Arc.	Spark.	Chromosphere. λ.	Intensity. 1926.	1905.	Blends. λ.		Intensity. Arc.	Spark.
				1^2F-1^2G.					
3952·42	2	1	—	—	—				
4118·78	10	20	·65	3	5N	*Fe*	·55	4	5
4121·33	20*u*	20	1·31	(3)*	3	**He*	0·81		
				1^2F-2^4G.					
+3811·07	2	1	(0·87	1	2)				
+3885·28	2	1	(·05	1	0)	*Cr*	·22	4	5
3965·02	1	1				*Ca*+	8·47	300	500
3995·31	20	20	·30	—	3				
4045·40	8	5	·36	—	2				
				1^2F-2^2G.					
3745·50	4	10	(·73	15	20)	*Fe*	·54	20	7
						Fe	·90	10	7
3845·48	20	30	·38	2	3				
3894·08	15	30	·19	1	2				
				1^2F-1^2D.					
3842·06	8	10	1·96	1	2				
+3861·17	5	10	(·38	2	3N)	*C*	·55		
3998·54	1	—	—	—	—				

A number of other multiplets may be present, but owing to blends the evidence for their presence is inconclusive.

The following are represented by their strongest lines only:—

				1^4F-1^6G.					
+3909·94	5*r*	4	·91	1	—	*Ba*	·92	50	10
+3979·52	4	4	·42	1	2				
4027·04	4	3	·20	—	0	*Zr*	·20	5	3
4057·20	3	1	·09	—	1				
				2^4F-1^4G.					
3808·11	3	3	·08	—	2N				
+3876·84	5	5	·75	1	1				
3906·30	3	3	·54	3	2	*Fe*	·48	8	5
+3941·73	5	4	·85	2	—				
3978·66	3	3	·59	—	0				
3991·69	3	3	·64	—	2				

Cobalt (27).—*continued.*

λ.	Intensity. Arc.	Intensity. Spark.	Chromosphere. λ.	Chromosphere. Intensity. 1926.	Chromosphere. Intensity. 1905.	Blends. λ.	Blends. Intensity. Arc.	Blends. Intensity. Spark.
				2^4F-2^2G.				
+3395·38	8	5	·43	1	0			
+3412·23	10*u*	4	·41	1	0	*Co* ·64 (1^4F-1^4D).	10	3
				$2^4F-1^2F'$.				
+3490·74	3	1	(·55	4	3)	*Fe* ·58	20	6
+3521·57	3*u*	5	·72	0	0			
3558·78	3	2	(·48	5	2)	*Fe* ·52 *Sc*+ ·55	10 10	6 10
3605·37	4	3	(·35	4	3*d*)	*Cr* ·34	30*u*	10
				2^4F-1^2G.				
3417·80	2	2	·89	1	—	*Fe* ·85	4	3
3496·68	3	3	(·92	2	1)	*Mn*+ ·81 *V* ·94	1 2	3 7
3564·95	5*r*	4	(5·37	5	4)	*Fe* 5·39	20	8
+3627·81	5	4	·82	1	1			
				1^2F-2^2D.				
3489·40	20	8	·41	—	0			
3518·35	10	8	·36	1	—			
				$1^2F-2^2F'$.				
3569·38	20	10	·43	1	3			
3587·19	15	10	·19	—	1	*Fe* 6·99 *He* 7·28	8	5
				1^4F-1^2G.				
3132·21	2	1	(·05	10	)	*Cr*+ ·04	4	10
+3191·30	2	1	·42	1				
3237·03	3	2	(·33	1	)	*Fe*+ ·40	—	1

The other multiplets of *Co* that might be represented in the range of the spectrum studied by us, and for which no evidence is found on our plate, may be grouped as follows:

$2^4F-2^4F'$
1^4F-2^4D
1^4F-2^4G
2^4F-1^2D
$1^2F-2^4F'$

which have lines strong enough in the arc to make their presence in the spectrum probable. Of these, only the first named is completely masked by blends with other lines; the stronger lines of the rest of the above multiplets are missing on our plate. The other group of missing multiplets consists of multiplets whose lines are all weak in the arc; they are

1^2F-3^4D	$1^2P-3^4F'$
$2^4F-2^2F'$	1^4P-3^4D
2^4F-2^2D	$2^4F-1^4F'$
1^4F-1^2D	1^4F-1^6D
$1^4F-1^2F'$	1^2F-2^4D
$1^4P-3^4F'$	2^4P-3^4D
$2^4P-3^4F'$	

It should be added that this investigation was made possible by a grant from the Government Grant Committee of the Royal Society.

On the Spectrum of Comet Pons-Winnecke (1927c). By G. Shajn.

It has long been recognised that comets are very difficult objects for spectroscopic observations. It is especially important to obtain a series of spectra of the same comet covering a long period, so as to investigate variations of the spectrum in relation to variations of the comet's brightness and the changes in its aspect. This emphasises the importance of securing observations of faint comets with objective prisms at the earliest date when an impression can be secured. Periodic comets have a special interest. The apparition of comet Pons-Winnecke in 1927 allowed me to obtain a series of such observations. Obviously the unusual rapid motion of this comet was unfavourable for such an investigation. Owing to the faintness of the comet and its rapid motion, it was impossible to carry out this study with all the precautions which are necessary in spectro-photometric work. For this reason I am able to give only the relative intensities of various parts of the spectrum and their changes.

The scale of the spectrum is small, as the focal length of the objective (Tessar) is only 24 inches and the prism has an angle of 17°. The distance from H_β to K is only 4·05 mm., whence it is evident that but a slight degree of accuracy can be expected in the determinations of wave-lengths. Eight satisfactory plates were obtained up to 1927 June 30, when the comet was too far south for further observations. The first plate was obtained on May 21, but no trace of an impression due to the comet could be detected. The comparison of the plates shows considerable differences of a regular character. Three maxima about 388, 405, and 469$\mu\mu$ are recognizable, and on the first plates of May 30 and June 1 a very faint fourth maximum about 428.

The maxima do not appear as bands well defined towards the red, but gradually shading off towards the violet, which is a well-known

characteristic of the bands of hydrocarbon. The wave-lengths were measured with the stereo-comparator. The comet's spectrum was compared with that of a star obtained immediately before and after the exposure on the comet's spectrum. Superposing the images of the stars on that of the comet and employing a Hartmann formula I was able to measure the wave-lengths of the maxima in the comet's spectrum. Owing to the diffuse character of the images and the small dispersion, the degree of accuracy is very small. I give below the wave-lengths of these maxima measured on the plates of May 30 and June 1.

Edge . .	3927	4080		4720
Middle . .	3885	4046	428 ?	4690
Edge . .	3860	4020		4670

These maxima are known, and they have been found in some comets by Frost and Parkhurst, A. de la Baume Pluvinel and Baldet, Campbell and Albrecht, Wright, Sampson, and Storey, Deslandres and Bernard, Evershed, Wolf, Curtis, Chretien, Rosenberg, and others.

The first band is unquestionably the third cyanogen band. For the others I give the simple designation "*carbon.*"

The main interest of these observations lies in the establishment of the variation in the spectrum of the comet from May 30 to June 30. Obviously only the relative intensities need be considered, leaving aside the question of the absolute variations of separate maxima and continuous spectrum from one day to another. The faintness of the comet and its rapid motion is responsible for the impossibility of carrying out detailed photometric work. In Table I. and fig. 1 the results of estimates of the brightness are represented. The most dense portion of the spectrum is estimated by 10, the clear film by 0.

Table I.

Date. \ λ.	384.	388.	397.	405.	419.	434.	450.	469.	479.
May 30	0·5	10	0·5	5	0·5	0·5	0·5	3	0
June 1	0·5	9·5	1	10	1	1	1	5	0·5
4	0·5	10	1	8	1·5	1·5	1·5	2·5	1
8–9	0·5	9	1·5	10	2	2	2	5	1·5
22–23	0·5	6	1·5	10	2·5	3	3	7	2
23–24	0·5	4·5	2	10	3	4	4	7	1
26	0·5	3	1·5	10	5·5	5·5	6	9	3
30	0	2·5	1·5	7	5	5	5	10	3

The following features of the comet's spectrum may be noted.

1. During the first few days, May 30 to June 4, the brightest maximum was at 388, while that at 405 was a little fainter and that at 469 sensibly fainter. On the plate of June 1 there is a trace of 428. It may be noted that on May 30 there was no evidence of the presence of a con-

tinuous spectrum. On the following days June 1–4 there was a trace of the continuous spectrum.

2. In the period June 8–24 the maximum at 405$\mu\mu$ was the most important feature of the spectrum. The intensity of 468$\mu\mu$ increased. The intensity of the continuous spectrum also increased.

3. In the period June 26–30 the maximum at 388 was the faintest, the most important being 468$\mu\mu$, though 405$\mu\mu$ was also bright. The continuous spectrum became very intense, surpassing the intensity of 388$\mu\mu$.

I am unable to account for the photographic effect of the variation

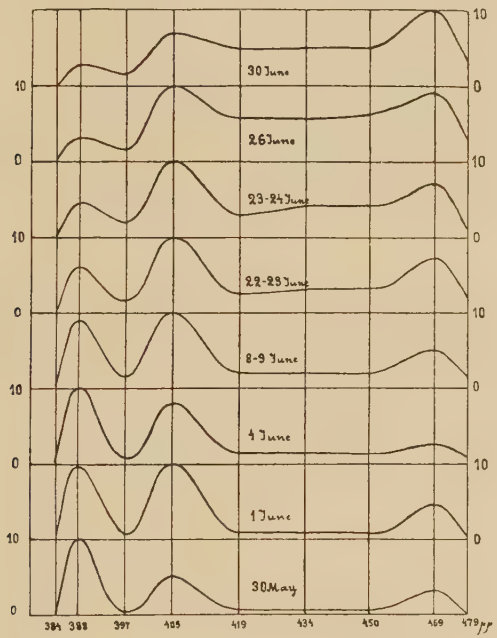


Fig. 1.

of the brightness of the comet and the time of exposure. As for the time of exposure it was practically the same for May 30–June 8 (about 100^{m}). The variation of brightness of the comet during this period was very small. However, a sensible variation in the spectrum took place during this period. The time of exposure, June 22–30, was also nearly constant (about 40^{m}); the variation in brightness was rather large, and there was a sensible change in the spectrum. But owing to the narrowness of the portion of the spectrum used (between 382 and 485$\mu\mu$), I consider that the changes in the spectrum were not due to variation of the factor γ with the wave-length, but to real variations in the relative brightness of the maxima and continuous spectrum. The estimates of the brightness are not corrected for

atmospheric extinction. But it should be noted that the majority of the plates were taken at small zenith distances. The only sensible influence of atmospheric extinction was for the plate of June 30. But comparison with the plate of June 26 shows that the results are not seriously affected by the atmospheric extinction. Owing to the faintness of the comet and also its rapid motion, only low density spectra were obtained, except on June 26, when low and mean density spectra were obtained. The comparison of these plates shows that the relative estimates of brightness are not seriously affected by the influence of the intensity. All the plates (Ilford Monarch) were taken with the same focus, and were developed in a uniform manner (5 per cent. Rodinal, 6 minutes).

The variations in the spectrum (fig. 1 and Table I.) are such that the maximum of the intensity was gradually displaced towards longer wave-lengths. I think that the increase of the brightness of the comet for visual rays was more rapid than that for photographic ones. Obviously the colour of the comet should change from bluish to whitish-yellow. It seems probable that this rapid displacement of the maximum to the longer wave-lengths is responsible for the great visual brightness of the comet during the last days of June, in excess of the computed change.

There is another point to be noted, namely, the relation between the intensity of the maxima and continuous spectrum. It must be remembered that the distance of the comet from the Sun was nearly constant during the period May 30–June 30 (1·08 to 1·05), whereas the distance from the Earth was 0·217 on May 30 and 0·046 on June 30. There is no doubt that the brightness of the continuous spectrum increased to a larger extent than that of the maxima. Since the distance from the Sun was constant, it follows that, during the period mentioned above (rapid approach to the Earth), the conditions responsible for the continuous and the band spectrum changed in the comet in different manners.* This fact must be emphazised. It must also be noted that the width of the monochromatic maxima was generally larger than that of the continuous spectrum, especially in the second half of June.

* I have not taken account of the influence of phase.

Simeis, Branch Observatory of Pulkovo :
1927 *July* 22.

LIST OF ADDITIONS

TO THE LIBRARY

OF THE SOCIETY

1926 JUNE 30 TO 1927 JUNE 30.

Serial Publications received in the regular course, and Reprints of Papers published in some of these Serials, are not included in this Annual List.

An asterisk (*) indicates that the work is an excerpt.

Abetti (Giorgio):

—— : *Relazioni fra fenomeni solari e terrestré.
(*Arcetri Observatory.*) 8vo. [*s.l.*], 1927

Andel (Karel):

Mappa Selenographica, with key-map and index.
(*Czech Astronomical Society.*) 2 folio sheets, Prague, 1926

Andoyer (Henri):

—— : La théorie de la lune.
(*Author.*) 8vo. Paris, 1926

—— : Sur la théorie analytique du mouvement de la lune.
(*Author.*) 4to. [Paris], [1926]

—— : Cours de mécanique céleste. Tome 2.
(*Purchased.*) 8vo. Paris, 1926

Apian (Peter):

Sternkarte, Ingolstadt 1536. Unicum. Neu herausgegeben von Ludwig Rosenthal's Antiquariat, München.
(*L. J. Comrie.*) 1 sheet [München], [1927]

Aquino (Radler de):

—— : *" Wrinkles " in Plane Chart methods.
(*Author.*) 8vo. Menasha, 1914

—— : *Navegação e Aeronavegação.
(*Author.*) 8vo. Rio de Janeiro, 1924

—— : *Novissimas Taboas para achar Alturas e Azimuths.
(*Author.*) 8vo. Rio de Janeiro, 1924

Arcetri, Osservatorio Astrofisico:
Immagini Spettroscopiche del Bordo Solare osservate a Catania e Zurigo nel 1922–23. [Unione Astronomica Internazionale.]
(*Observatory.*) 4to. Firenze, 1926

Astronomy: A Revision of Young's Manual of Astronomy.
See Russell, Dugan, and Stewart.

Australia, Pan-Pacific Science Congress:
Proceedings, 1923. 2 vols., 8vo. Melbourne, 1923
(*Council for Scientific and Industrial Research.*)

Bamberg, Remeis Sternwarte:
——: Heliozentrische Minima der Bedeckungsveränderlichen für 1926, von Eduard Heise.
(*Observatory.*) 8vo. Bamberg, 1926
——: Katalog und Ephemeriden veränderlicher Sterne für 1925.
(*Observatory.*) 8vo. Leipzig, 1924

Baxandall (D.):
Calculating Machines and Instruments. (Catalogue of the collections in the Science Museum, South Kensington, with descriptive and historical notes and illustrations. Mathematics I.)
(*Director of the Science Museum.*) 8vo. London, 1926

Berlin, Preussische Akademie der Wissenschaften:
Geschichte des Fixsternhimmels.
(*Purchased.*) 4to. Karlsruhe, 1926
Abteilung I., Band 5. 4^h Rektaszension.

Berlin-Babelsberg, Universitäts Sternwarte:
Kleinere Veröffentlichungen, Nos. 1, 2.
(*Observatory.*) 8vo. Berlin, 1926–27

Besançon, Observatoire National Astronomique, Chronométrique et Météorologique:
Bulletin chronométrique, 26–29 (1913–1924).
(*Observatory.*) 4to. Besançon, 1925

Beyer (Max):
Stern-Atlas, enthaltend alle Sterne bis zur 9^{ten} Grösse, sowie die helleren Sternhaufen und Nebel zwischen dem Nordpol und 23° südlicher Deklination für 1855·0 . . . herausgegeben von Prof. Dr. K. Graff, Observator der Hamburger Sternwarte. Plates 1–27.
(*Purchased.*) Fol. sheets, Hamburg, 1925–27

Bigourdan (G.):
*Mélanges Scientifiques, Nos. 23, 24.
(*Bureau international de l'heure.*) 4to. Paris, 1926

Biot (Jean Baptiste):
——: Mémoires. (Collection of reprints.)
(*Bequeathed by the late Dr. Dreyer.*) 4to. Paris, 1818–1860
——: Mélanges d'astronomie. (Collection of reprints.)
(*Bequeathed by the late Dr. Dreyer.*) 4to. Paris, 1846–1861

Boccardi (Jean):
*La rotation des planètes intérieures.
(*Author.*) 8vo. Paris [1926]

Bombay and Alibag Government Observatories:
Magnetical, Meteorological, and Seismographic Observations, made . . . in the years 1921, 1922.
(*Observatory.*) 4to. Bombay, 1926

Bordeaux, Observatoire:
——: Carte photographique du Ciel. Zones +12°, +14°, +16°. (22 Charts.)
(*Observatory.*)
——: Catalogue photographique du Ciel. Co-ordonnées rectilignes. Tome 5. Zone 12° à 14°.
(*Observatory.*) 4to. Paris, 1925

Bourgeois (P.):
*Recherche sur le mouvement d'étoiles voisines du soleil.
(*Author.*) 4to. Bruxelles, 1926

Bowie (William):
*Use of the Gravity Pendulum as a Time-piece.
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Captain J. H. Jones. A portable ivory string compass dial, by Hans Troeschel (Nürnberg, 1567–1612).

Dr. W. H. Steavenson. Framed photograph of Sir William Herschel's first 40-foot Speculum, discovered at Slough 1927 February.

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